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A Compositional Interface for Generative Audiovisual Systems

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by

Keehong Youn

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Education

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Research

Electron Wavefunctions in a Hydrogen-Like Atom: Simulation, Visualization & Sonifcation (2015 - 2018)

- Participation: Development of software for spherical projection mapping
- Sponsor: AlloSphere Research Group, University of California, Santa Barbara

Transmission Electron Microscope/Atom Probe Visualization (2015 - 2016)

- Participation: Visualization of atom probe and transmission electron tomography data
- Sponsor: AlloSphere Research Group, University of California, Santa Barbara

Brain Fusion: Study of performing Arts and Design Using New Technology (2013)

- Participation: Development of the real-time wind data network software
- Sponsor: Seoul National University Development Fund

Spatial interface for improving UX of car navigation system (2012)

- Participation: Development of the spatial interface using depth sensing camera
- Sponsor: Hyundai NGV

Home Rehabilitation System for Upper Limbs of Stroke Patient (2012)

- Participation: Development of the upper body tracking system using depth sensing camera
- Sponsor: Korean Ministry of Knowledge Economy and Microsoft Asia

Single Cell Addressing by Microscope Augmented Reality (2012)

- Participation: Hardware setup for utilizing multiple depth sensing camera
- Sponsor: Korean Ministry of Education and Science Technology

Publications

PROBABLY/POSSIBLY?: An Immersive Interactive Visual/Sonic Quantum Composition and Synthesizer

- JoAnn Kuchera-Morin et al.
- Proceedings of the 25th ACM international conference on Multimedia, 2017

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- Microscopy Research and Technique, Vol. 77, Issue 4, 2014

ElaScreen: Exploring Multi-dimensional Data using Elastic Screen

- Kyungwon Youn, Junbong Song, Keehong Youn, Sungmin Cho, Hyunwoo Bang
- SIGCHI 2013 Extended Abstracts

Abstract

A Compositional Interface for Generative Audiovisual Systems

by

Keehong Youn

With a digitally implemented generative system for artistic purposes, controlling a non-trivial number of parameters is one of the difficulties in the process of temporal composition with the system. Unless done manually for every keyframe in the duration of the work, a kind of interface that facilitates the process is necessary. This research proposes an interface for temporal control on parameters of the generative audio-visual system. The proposed interface operates in 'state space' formed by a simplex shape of arbitrary dimension with the barycentric coordinate to define the locations inside. Each vertex of simplex represents a reference point in the parameter space of the system. In this manner, regardless of geometric relation between reference points in parameter space, the artist can locate and use any mixed state of the reference states by simple interpolations. This decoupling of the relative coordinate of the states from the specific values of the parameters makes an abstraction for the artist to perform the manual design of the temporal structure efficiently. The state space is a connection between the generative system and the temporal control. With the proposed interface, three artworks are introduced as proof of concepts. *Reconstruction* is an installation piece, experimenting with virtual geographical shapes. The *Reconstruction* is a proof of concept that utilizes the state space model for its automatic control, hinting the possibility of a state space model for connection between the generative system and manual composition. *Balanced Movement* is a fixed length composition, using dynamic equilibrium from the stochastic system as the primary material of the visual. *Balanced Movement* utilizes state space

to define its manual temporal composition. *Wavefront* is an immersive audio-visual performance using a mathematical abstraction of an ocean wave as visual material. In *Wavefront* state space is used to spawn entities in performance time dynamically.

Contents

Chapter 1

Introduction

There are many different sets of terms used in various fields of art that point to a similar idea for composition of any spatial or temporal dimension: Order and Disorder, Continuity and Contrast, and Constructing Symmetry and breaking Symmetry. An effective presentation of contrasting structure gives the aesthetic quality that is appreciated. In traditional methods, it was carried out and designed by the artist manually. On the contrary, it could also be achieved by delegation to the computers [1]. Even though the field of generative art started with this idea of delegation, artists such as Xenakis adopts the mix of delegation and control to achieve the most of aesthetic quality in the artwork [2]. And this combination of delegation and management is not uncommon at all among the artists. In order to combine generative delegation and manual management for control, a appropriate method for connecting two different approaches is needed. While many different methods exist to connect generative systems and manual control, this research aims to bring a new novel approach that maximizes the benefits from both generative control and manual control while ensuring the high productivity of the artwork creation process.

1.1 Generative Art

1.1.1 Delegation of control

When a generative method or a formal method is used in an artwork, it denotes that during the creation of the work, certain parts of the whole process are not directly manipulated or controlled but rather are derived from a set of rules or a logic structure, "which is set into motion with some degree of autonomy contributing to or resulting in a completed work of art." [3] Galanter brings complex theory as a context for analyzing generative methods. In this view, concepts such as self-organization, complex system, chaotic behavior, randomness, and the stochastic process can be brought together. With these systems, 'Emergence' is the term used to describe cases where the result of a system is especially meaningful, interesting, unexpected, and hard to reason its causality. Some artists adopt these methods to completely or partially delegate the art-making process. This concept of delegation, also termed as the 'negation of intentionality'[4], plays important part in motivation of those art-making process: "Generative art is interested in generative processes (an in software or code) only insofar, as they generate "unpredictable" events" [4]. These rule-driven systems offer automated processes producing the result (conforming the rule given by the artist), in contrast to manual decisions done by the human artist alone. Boden and Edmonds discuss the definition and the characteristics of generative art in depth [5]:

> "Both in music and visual art, the use of the term has now converged on work that has been produced by the activation of a set of rules and where the artist lets a computer system take over at least some of the decision-making (although, of course, the artist determines the rules)."

> "Rules are at the heart of this type of art. But what computer scientists

> call rule-based programming (e.g. Kowalski and Levi 1996) is not necessarily implied. The computer-art community regards it as important that the artwork is generated from a set of specified rules, or constraints, rather than from a step-by-step algorithm. But the detailed implementation method (i.e. the specific computer system that's being used) is not normally seen to be significant."
>
> "To understand this point, consider an oversimplified illustration of the programming concepts just mentioned. When a program is written in an step-by-step (algorithmic) way, the programmer instructs the computer to "do A", then "do B", then under certain conditions "do C", otherwise "do D" and so on. When a programmer writes rules (constraints), however, they tell the computer that (for example) "Z should always be bigger than Y", "X must never equal W", and so on —but they leave it to the computer system to work out how to apply those rules."
>
> (...)
>
> "In G-art, (df.) the artwork is generated, at least in part, by some process that is not under the artist's direct control"

As of today, there is an increasing number of generative artworks with different styles and structures. Among those, one of the common formats that are used is the digitally implemented audio-visual artwork that aims to visualize and sonify different kinds of a generative system over time. This format of art: 'time-based digital audio-visual generative artwork' will be mainly discussed in this research.

1.2 Research Motivation

1.2.1 Need of control

In this research, the generative systems are used as the primary material of the artwork. Emergence will be expected to play a critical role in the aesthetic quality of the works. It involves the design of a new system and observation on how it behaves. The artist will try to design a system that could present unusual emergent behavior. In Lozano-Hemmer's interview, a similar way of artwork creation is mentioned [6]:

> "Most electronic artists are looking for an out-of-control quality that will result in their work actually having outcomes that they did not anticipate. If the piece does not surprise the author in some way then it is not truly successful in my opinion."

Although the critical aspect of generative art is to give up control to the rules and logic, there is still some room for explicit manual controls from the artist. Note that in the previous statement of generative art, there is no specific statement on how much control should be delegated to the generative method. How much and where should the control be given up or maintained is one of the main concerns in terms of the aesthetic quality of the work. Depending on the ratio of this mixture, the success of an artwork could be significantly affected. If the artist tries to input too much control to the generative system, the interference might hinder the system from showing the aesthetic of delegation and not produce any impressive results. On the contrary, if there is almost no control at all, the chances of emergence being created are as low as the chances of life being created in the primeval soup. In the article by McCormack and Dorin, an example of a failed experiment with the generative system is suggested [7]:

> "By Brown's own admission, the work "did not produce any surprising emergent results". Adding complexity to the rules and simulated physical phase space of Biotica resulted in a more complex system, but not in results that created new levels of surprise, agency or novelty."
>
> "Sim's virtual creatures on the other hand, do indeed produce novel and surprising results, but are they truly emergent? Sims designed a specific low-level infrastructure to support his con- scious goal of creating block-like creatures that discover, via competitive evolution, solutions to specific goals (following lights, competing for objects), rather than spontaneously emerging."
>
> (...)
>
> "In a design sense, it is possible to make creative systems that exhibit emergent properties beyond the designer's conscious intentions, hence creating an artefact, process, or system that is "more" than was conceived by the designer. This is not unique to computer-based design, but it offers an important glimpse into the possible usefulness of such design techniques – "letting go of control" as an alternative to the functionalist, user-centred modes of design. Nature can be seen as a com- plex system that can be loosely transferred to the process of design, with the hope that human poiesis may somehow obtain the elements of physis so revered in the design world. Mimicry of natural processes with a view to emulation, while possibly sufficient for novel design, does not alone necessarily translate as effective methodology for art however."

Following the idea of the phrase "while possibly sufficient for novel design, does not alone necessarily translate as effective methodology for art however" from above quote, this research begins with the assumption that the kind of failure Brown in the quote faced is caused by the lack of proper control over the system, just letting the system run without any management. Without management or control, there is a very high probability that it might not produce any interesting result since the value of emergence comes from its rare chance of appearance. This assumption leads to the question: "How can the artist effectively balance control over the generative system?". The proper amount of control over the generative system should make it possible to expose the full aesthetic potential of the generative system, while not restraining the autonomy and self-organizing characteristic of the system.

1.2.2 Creative process with balance between delegation and control

To proceed with this combination of delegation and control, a boundary needs to be set between them in the creative process. While there could be more detailed classification, this research divides the creative process largely into two levels. The process of the lower level is the creation of generative material, where the generative behavior of interest is implemented. The artist sets up the system so that it can respond to different inputs and parameters and produce the material of the work. How the generative system will be controlled is determined at a higher level. With a broader perspective, the artist will define how the artwork's material will unfold in time and space. This higher level process of creation can be thought as the act of composition, while the lower level creative process can be thought of as materialization, or crafting of the instrument. This idea aligns with a note from Dahlstedt: "formal methods works best at the lower levels, for material and structure generation" [8]. While Dahlstedt differentiates the four levels of music composition (sound design, material generation, structure generation, and generation of the large-scale form) 1.1, he states that for higher level compositions manual control is more suitable. Though Dahlstedt's domain of interest was music composition, the general idea

- Sound design — *Generating source material on the lowest level.*
- Material generation — *Processing the source material.*
- Structure generation — *Putting together the processed material.*
- Generation of large-scale form — *Assembling and shaping the parts of the piece.*

Figure 1.1: Four levels of music composition by Dahlstedt [8]

should apply to the domain of interest in this research: time-based generative audiovisual artworks. It is not hard to find audiovisual works that adopt the generative aspect for materialization and manual control of the artist for temporal structure, examples of those will be discussed in the following section, *Historical Background*.

Following the statements mentioned above, this research divides the creative process for time-based audiovisual generative artworks into two different parts. The first part is the creation of the system, where the generative behavior is implemented. Creating a system generatively is "selecting a structure to which the work will conform, such as an algorithm determining the form." [9]. The other part is the higher level of control over the system. The artist can work on the compositional process at this level by specifying the inputs to the system. The inputs to the system are more often called parameters. The boundary between these processes does not need to be precise and clear. For some cases, there could be overlap or integration between them.

With these observations, the motivation of this research comes from the need of finding a proper balance between delegation and control. To effectively present the generative system aesthetically, the artist needs to reveal the most emergent behavior of the system over time and space. This temporal control process relates to compositional ideas and techniques. However, it is not a trivial task to apply those compositional ideas due to the characteristics of the digital implementations of the materials. These difficulties are the problems this research tries to solve.

1.3 Problem Statement

1.3.1 Navigation in parameter space

Applying control on top of the generative system is the goal of this research. The content and implementation of the control will have the compositional idea the artist wants to realize. While the main activity of the compositional process is to form structures, movements, and narrative that artist intends to create, applying those to the generative system as forms of a digital signal is another essential and non-trivial activity. It is a task of translating compositional ideas into something that a computer program, the generative system, can take as input: the parameters. Hence the creative process of controlling a generative system consists of designing the compositional idea and finding the suitable parameter values that correspond to the idea. While the compositional idea and intention of the temporal structures of the composition can vary from work to work and artist to artist, the process of managing parameter values is common task for the artists trying to work with a digitally implemented generative systems.

This task of finding desired values of parameters are often called navigation or explorations in the parameter space. The term parameter space relates to how multiple orthogonal parameters of the system form multi-dimensional space by each being a unique axis of the space (figure 1.2). The number of independent parameters is the dimension of the parameter space. Also, note that the unit and scale of axes do not need to be the same. Because creating a composition is an iterative process, the navigation needs to happen a large number of times. Similar to the term REPL in computer programming, which stands for "Read-Eval-Print-Loop", the artist's workflow will be "set parameter, run the program, check the result, and repeat". With a large number of parameters and a wide range of each parameter values, it becomes difficult to quickly and effectively explore the space and navigate in it. Especially, it is not easy to intuitively find values for different axes when the unit of each axis is different. The existence of an interface that facilitates navigation and exploration in the parameter space of a given generative system would substantially help artists focus on the primary goal of the composition and play a critical role in productivity. This situation shows the problem this research intends to solve: a novel method for navigation in parameter space. This research tries to solve this problem by proposing a novel method and interface for manually controlling parameters in the temporal domain that can easily scale in the number of parameters one can control. It will facilitate the navigation and exploration in the parameter space of the given generative system.

1.3.2 Temporal structure from parameter control

In a more detailed way, the problem of interest consists of two parts. The first one is the process of finding appropriate parameter values. The second part is how to change or morph the parameters in time to shape the temporal structure of the work. For the finding of the proper values, there have been approaches such as GUI base controls or randomized parameter set generation [10]. For the temporal change of the parameters, the most popular approach is the combination of keyframes and shaping/tweening/easing functions [11]. These two different activities are both a critical part of managing the parameters of a system. Borrowing phrase from Tubb et al., they are “divergent exploration and convergent optimization”[12]. The artist needs methods to explore different parts of the parameter space, while also needing specifying the accurate parameter values that are needed for implementing the compositional idea. The proposed interface in this research tries to connect these two problems and tie them in one interface. Also, it does not try to exclude previous methods, which will be introduced in the following section, *Historical Background*, but rather create a common ground for bringing existing methods into the workflow. This research aims to provide an encompassing way of thinking and practicing for the whole creative process. Lastly, One thing to clarify is that the word 'interface' here denotes the interface in terms of programming language (e.g., library interface) that abstracts a mathematical scheme for managing the parameter values. The term interface in this research does not relate to user interfaces such as GUI (Graphical User Interface) or HID (Human Interface Device).

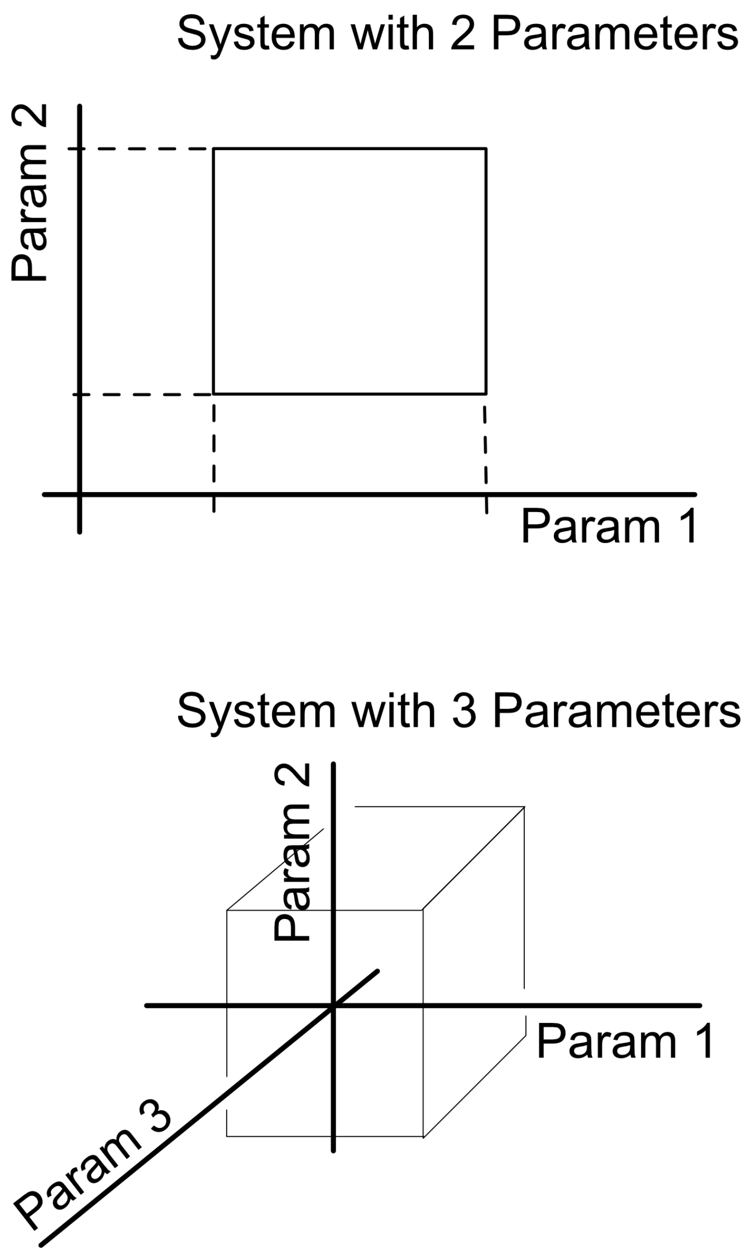


Figure 1.2: An example illustration of a possible parameter space, top: parameter space with two parameters in a system, bottom: with three parameters

1.4 Hypothesis

The hypothesis of this research is:

> Effective interface for the manual temporal control can provide greater potential in aesthetic quality to generative audiovisual artworks.

This research will present a series of works that utilized the proposed interface. First work *Reconstruction* is the very first work that works as a proof of concept how the proposed interface can be used. The following two works *Balanced Movement* and *Wavefront* tries to fully utilize the compositional potential of the interface.

1.5 Outline of the Dissertation

Chapter 2, *Historical Background* presents brief overview on not only previous art practices involving generative art, but also on the academic research done for the topic of this dissertation: parameter control. Chapter 3 *Methodology* provides background knowledge, a proposed concept, and a usage scenario of the proposed interface. Chapter 4 *Practices* presents three works that utilizes the proposed interface. Lastly Chapter 4 evaluates and discusses the works done and makes a note on future direction.

Chapter 2

Historical Background

This chapter covers historical works and studies that give ground to this research. First the history of generative art is introduced. After describing the beginning and motivation of the generative art, the works that mix delegation and control are listed. Those works to be introduced show that balancing the delegation and control is a existing problem while also suggesting the need of parameter control methods. Secondly academic studies on the parameter control are referred. Many of the studies are from computer music domain, due to the need of control on synthesis and instrument parameters for compositions and performances.

2.1 Previous Art Practices

2.1.1 New method of art creation

While there are many different definitions of generative art, many of the enable bringing in the works that was made much before the term was coined: "Generative art is as old as art" [3]. However, it would be more adequate to only focus on those of recent, after the 20th century, considering the scope of this research.

The progress of science and technology has always had a close relation to practices in art and music. As science and technology on complex theory such as self-organization and stochastics rapidly developed in the mid-20th century, artists and composers more and more focused on those scientific/mathematical principles of the complex theory as their material, instrument, or compositional method. Artists could explore creative possibilities with different methods of expression, unprecedented materials, and new ways of thinking. The movement of integrating scientific/mathematical concepts and technological materials into art and music was accelerated with the advent of electronics and computers. Even more materials such as an analog/digital synthesis sounds, plotter drawings, and computer-generated graphics became available with progress in electronic and computer media. The digital instruments were especially well suited for implementing complex systems.

The different methodologies of artwork creation also emerged. With the help of the computational platform, artists could run experiments for their thought processes effectively without constraints in space or time. Since then there have been various creative pursuit in generating art with mathematical rules, logic processes, self-organizing systems, or systems that follow laws extracted from natural phenomenons. These approaches in common give up control over a certain part of the creative process to a non-human decision-maker, which in many cases is a computer program. The creative methodologies of relying on algorithmic processes were called generative methods and led to the formation of a category of art called generative art. While one does not have to use the computer to do generative processes, computers indeed give a great power for implementing rules and the logic desired, and therefore computers were heavily used since the earliest days of generative art.

2.1.2 Iannis Xenakis

One of the early pioneers in the 1950s in this exploration is Iannis Xenakis. With his stochastic composition Pithoprakta, he showed how one can create a composition out of scientific laws and mathematics. The work was based on the thermodynamic statistical characteristics of gas molecules under the Maxwell–Boltzmann distribution [2]. He did not use the computer to calculate these generative systems, but rather do the stochastic calculations by hand. It is important to note that while he used the generative method to generate his material of the work and also to shape the movements, the structure of the work on the highest scale was still controlled by his hands. The outcome of the generative system was shaped by his large scale design.

2.1.3 Georg Nees and Frieder Nake

In the 1960s, Georg Nees started creating plotter drawings with his computer program that implemented different rules and operations to achieve a unique aesthetic quality [13]. Similar work was done by Frieder Nake, who experimented with his knowledge in probability theory [1]. In Nake's creative process the computer played enabled an important role by providing the artist with pseudorandom-number generators. Even in these static visual works, the artist's manual selection was an important process in the creative process. Experiment iteration and the selection was the main workflow, which shows that the manual final touch of the artist is still relevant even for the works that seem fully generative. Other notable artists from the same era are Michael Noll, Vera Molnar, and Manfred Mohr [14, 15, 16]. Just like Nees and Nake, they were using computers for experimenting with different algorithms to create aesthetic outcomes.

2.1.4 Time based digital audio visual generative artwork

Early visual works in generative art mostly started as static pieces, but it was not unexpected that progress in computing power and computer graphics made artists create time-based works. When these time-based generative visuals are combined with sound, the artwork gets placed into the intersection between generative art and audiovisual art. Edmonds states [17]:

> "Not surprisingly, painters quite frequently aspire to being composers or musicians. Formally, the distinction between seeing and hearing aside, the key difference between painting and music might be seen to be the presence of time as an integral element or dimension."
>
> (...)
>
> "Generative works of this kind lend themselves to the automatic generation of a series because the computer program is a kind of general structure or form that can apply to a class of works, each a variation of another. It seems natural to extend such explorations to time-based visual art."

With the time-based form of art, the design of a temporal structure, or composition, is inevitable. Designing the temporal structure for generative arts is the process of deciding the method of control. The following works show how the generative system can be controlled to create a time-based audiovisual work. Artists from different domains are introduced. Larry Cuba is a visual artist working with animations, while Kuchera-Morin has her roots in the music composition. Putnam is a digital audiovisual media artist, which is the domain this research also belongs to.

2.1.5 Larry Cuba

Larry Cuba created films with generative visual created by computer programs, unfolded them in time with manual composition. The basic elements that follow a simple rule in motion, are introduced in time and placed in the screen space. A simple motion of an individual element becomes a building component of the whole scene. The group of spawned motions form a more complex composition, as the visual of each element overlap and cross with those of others. The audio corresponding to the visual also adds up as those elements come into the scene and go out of the scene. All these complex generative behavior is structured and placed in time by the artist's manual control.

2.1.6 JoAnn Kuchera-Morin et al.

An immersive audio-visual composition Probably/Possibly? by JoAnn Kuchera-Morin, Luca Peliti, and Lance Putnam [18] is a combination of traditional composition and a digital generative system. The generative part of the system is a simulation of quantum mechanical wavefunction using solutions of the Schrodinger equation. The wavefield of electron deforms the rubber-like simulated virtual structure, resulting in the complex shape to emerge. The simulation result is interpreted into visual and sound, enabling the artist to make a composition on top of the system. By changing the parameters: the quantum numbers of the equation, the composer can control the system to output different visuals and different sounds. With this generative system set up, the artist writes a sequence of parameters to be played in a digital text file, which will be read and played by the system. Probably/Possibly? gives the ground this research stands on, in the context of having a generative system that is manually controlled for effective demonstration of aesthetic quality.

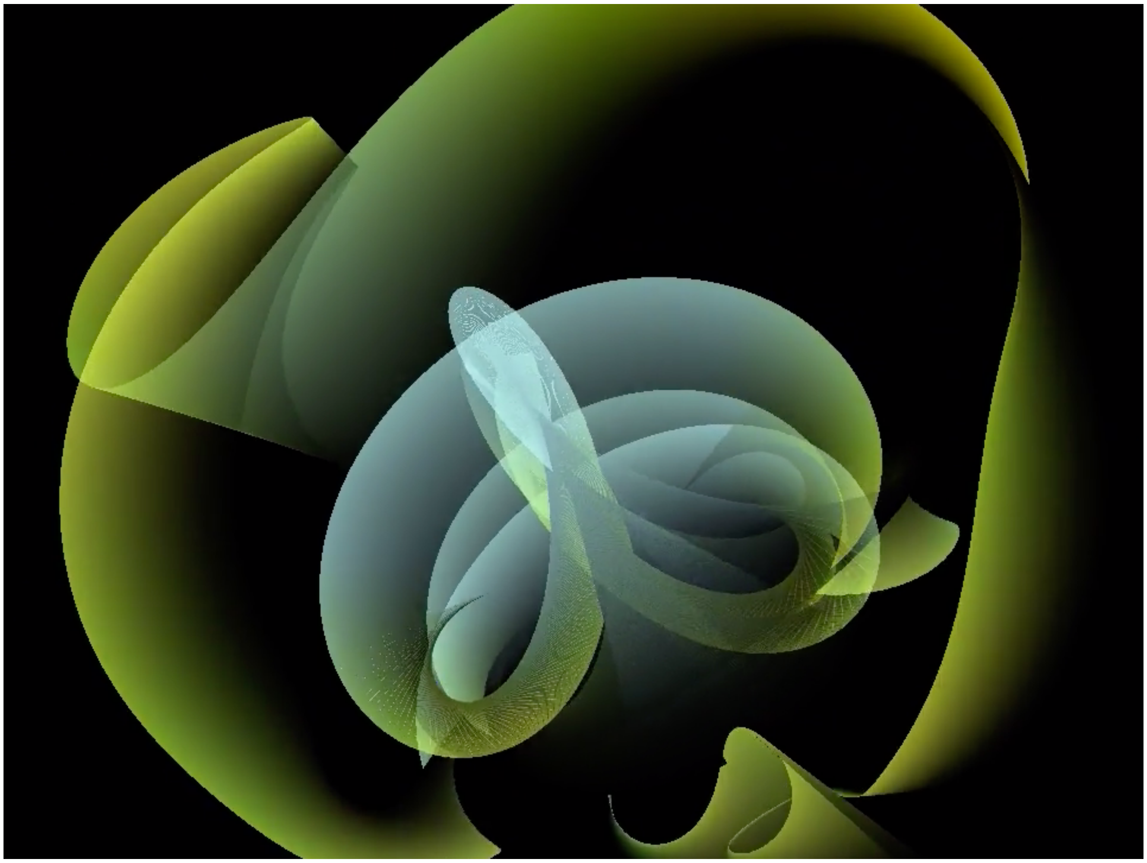


Figure 2.1: A frame from Probably/Possibly? [18]

2.1.7 Lance Putnam

MAT alumni Lance Putnam's Adrift [19] is a work that has a very similar structure to what this research pursues. The work is an immersive audiovisual to be exhibited in the AlloSphere facility [20]. The generative system of Adrift is a recursive iteration of transforms from matrix multiplication that generates a continuous sequence of coordinates. Depending on the coefficients of the matrix different outcomes are produced. While the matrix calculation shows linear behavior in small scale change, it is hard to predict which shape will come out with large scale differences in the input parameters. The temporal control on the system is done by interpolation of the parameter sets with a sequencer interface. The concept of parameter set and the construction of temporal control from interpolations between the sets are a core idea that connects this referential work and this research. The parameter sets are a specific point in the parameter space, and the interpolation between them creates a trajectory the system travels in the parameter space. More sophisticated discussion in this relation is also covered in the next section *Previous Research* with Putnam's other work *S Phase*.

2.1.8 Control with the generative system

The works so far introduced shows how great work can be achieved by properly controlling the generative systems. To control the digital generative systems, as mentioned in the introduction, a method to handle parameters of the system is essential. The next section of this chapter lists previous studies on how those parameters can be controlled.

2.2 Previous Research

There is also much academic research on the control of parameters for digital art. Most of them belong to the computer music domain, studied for compositions and performances. Note that they all in common tries to provide vector-based control in parameter space, being a starting point for this research. Other concepts that are common is the interpolation of the parameters and the mapping of the control signals to the parameter values.

2.2.1 Genetic evolution of parameters by Dahlstedt

Dahlstedt [21] proposes a genetic algorithm based interactive interface to control system parameters and help compositional process. The interface provides the user with a repeatable selection process for genetically bred sound objects. Here the genes for evolution are mapped to parameters of a midi system, making each genetically bred sound objects to represent a different combination of parameters. It is suggested that the interface "simplifies aural exploration of huge synthesis parameter spaces, and presents a possibility for the sound artist to create new sound engines."

2.2.2 Cross-modal parametric composition by Gerhard and Hepting

Gerhard and Hepting [22] categorizes the computer-aided composition, in contrast to algorithmic or automatic composition, that "provides algorithmic tools to composers, allowing them to interactively build new works." This point emphasizes the manual selection of the artist which cannot be substituted by any algorithmic automation while admitting that the existence of a 'helper system' could maximize the productivity and effectiveness of the creative process. An important idea in their research is how they consider the parameters as initially decontextualized objects that can represent any quality or process. This approach decouples the parameters from actual numbers and gives parameters functionality to represent state and movement: "parameterization allows a composer to work in the abstract without needing to realize the ideas or composition in any specific way." In this manner, the control signal becomes a representative of a certain compositional idea, not just a combination of parameter values or the values that will be mapped to the parameters. In their interface *Cogito*, parameters were the discrete variable that can have a number of possible values and the user could make a choice of different combinations of the values. Also with the selected values, the interface provides the functionality to create various transition paths to have control over the movements in composition. The specific points in the movements can be calculated with linear interpolations. This configurable transition path generation enables an additional degree of freedom in composition.

2.2.3 Logic programming by Edmonds

Edmonds [17] uses *logic programming* for composing time-based visual art. Logic programming resembles generative methods in the sense that it is rule-based, but differs in the fact that it is more explicit and deterministic. Logic programming is presented to be concise and productive in terms of thinking at the structural level. Edmonds states that "the explicitly defined part of the work is the structural element including, specifically, the rules that are to be used to determine in which order and at which pace the image sequence should stop. (...) Logic programming can be used as a method for handling structures in time." This model of the creative process presents the mixture of generative process and manual control. In the section *Practices*, a work with similar model *Reconstruction* will be introduced.

2.2.4 Design Galleries by Marks et al.

The Design Galleries [23] system seeks new methodology for finding input parameters that yield desirable output in the computer graphics domain. It enables the user to select within automatically generated and organized options, derived from the input parameter vector the user has provided. This system tries to be more automated and more dominant in parameter control compared to other methods mentioned above. It is due to the fact that this research is more focused on setting parameters for image rendering rather than artwork composition. Still, the way it defines constrained parameter space of interest by sampling neighborhood or evolving input vector is a notable approach. The important point of this reference is similar to the one by Gerhard and Hepting, showing that while the selection and control by the artist is the final decision maker, some kind of interface for productivity is essential for the successful creative process.

2.2.5 Intersecting N-Sphere Method by Marier

The sphere intersection method by Marier [24] uses radius based approach in arbitrary dimension to interpolate between different data points. The selected data points are placed in an arbitrary dimensional space and then when a data point is close enough to the interpolation point, i.e. when two spheres centered at the data point and the interpolation point overlaps, the data point is then included in the weighted interpolation equation. As the interpolation point move in the interpolation space, different interpolation points gets included in the list of points to interpolate, enabling the different result of interpolation. This method provides a continuously differentiable trajectory of the result and can be used with any number of dimensions.

2.2.6 High-dimensional interpolators by Goudeseune

Goudeseune [25] proposed the high-dimensional interpolator. The interpolator maps `M` dimensional control space to `N` dimensional parameter space (`M < N`) so that the dimensionality, or the degree of freedom, for the user is diminished. This dimensionality reduction is useful in terms of musical instrument design, helping the user to focus on the most important parameters only. To map the lower dimension information to the higher dimension, the method does an initialization step where the region in the parameter space is preprocessed to find out what are the neighboring 'desirable points'. After the initialization step, any point in the parameter space will have a list of 'desirable points' for interpolation. While running, the precalculated neighboring `M` 'desirable points' can be used as vertices to form a simplex with barycentric coordinates, then the 'simplicial interpolation', which is a weighted sum of values of vertices, can be used to map the lower dimension and higher dimension.

2.2.7 Manifold interface by Choi et al.

Choi et al. ([26]) uses 3D lattice-based arbitrary multi-dimensional space where control variables are parameterized. The original parameter space is divided into sections, which will be mapped to the 3D lattice of the 'window space'. The 'window space' is a space where then the artist can design the movements and structures intuitively (since it is a familiar three-dimensional space) to later map the temporal design to the original parameter space. The 'control path' in the 'window space' is mapped back to the 'phase space' of the system with 3D lattice-based mapping.

2.2.8 Metasurface by Bencina

Bencina [27] proposes a two-to-many mapping interface to interpolated between parameter snapshots placed on a plane: the “snapshot plane”. The parameter space is projected down to a two-dimensional plane, which will also be a graphical interface for the user. The user can pick a point in the plane then the Metasurface system can calculate the mapped parameter values in the original parameter space of the instrument. The Metasurface uses natural neighbor interpolation which finds the number of closest neighbor points based on Voronoi tessellation and then interpolates them with different weights depending on the position of the point of interest on the snapshot plane. It is claimed that while it is a dimensionality reduction technique, the metasurface model effectively represents multi-scale surfaces on the snapshot plane.

2.2.9 S Phase by Putnam

While working on his piece S Phase, in order to control “a single abstract signal that could be instantiated into aural and visual representations” Lance Putnam designed a GUI based compositional score interface that traverses through different parameter sets [28]:

> “The score for the piece is a sequence of parameter state spaces with different interpolation curves and durations between them. The state spaces can be likened to the notes and the interpolation the work going from one note to the next. The piece is effectively the journey taken between specific points of interest.”
>
> “To actually compose the piece, I made an interactive editor to control all the compositional parameters with sliders and save presets of parameters. The parameter editor lets you use sliders to change values or enter exact values

> with the keyboard. Several parameters, such as translate and rotation, can also be controlled with the mouse."
>
> (...)
>
> "This composition system was designed to make this piece, however, it is general-purpose enough to be used to create "paths" through other parametric systems."

This method is very effective and efficient in terms of creating a real-time control signal for 28 parameters he designed for the generative system.

2.2.10 Summary

Note that Putnam uses the interpolation between the set of parameters for forming the temporal structure. These transitions are happening inside the parameter space of the generative system, which dimension the same as the number of its parameters. This method stands on the same ground as a vector-based approach with previously mentioned studies. With `N` many parameters, the state of the systems is specified by a vector of `N` dimension. However, as the number N gets larger, if it were to control each dimension separately, the time and effort needed would be overwhelming. How Putnam solves this problem is by interpolating the vectors geometrically so that with one interpolation function, the values of every dimension would be calculated.

This is similar to other studies. Gerhard and Hepting [22] uses trajectories connecting 'key states', Marier [24] uses nearest spheres to interpolate between 'data points'. Goudeseune uses [25] 'simplicial interpolation' to interpolate between 'desirable points', and 3D lattice-based mapping is used by Choi et al. ([26]) to make 'control path'. This process of changing the parameters of a system is referred to as 'mapping', 'morphing', or 'interpolation'. Space, where original parameters lie in, is named as 'parameter space' or ‘phase space’. ‘Control path’ or ‘trajectory’ represents the timed sequence of the parameters in a space.

While some studies directly manipulate the parameters, reducing the degree of freedom is another topic in common in most of the research. By reducing the number of things the user has to control, the interface gains usability and intuitiveness while reducing complexity. When different dimensionality reduction techniques are used, the resulting lower dimensions are called ‘interpolation space’, or ‘window space’.

This research takes a similar approach to these studies. While most of the references were from the computer music domain, Putnam’s work shows how the parameters can be controlled in the context of the generative art domain. This research is an extension in the direction of Putnam’s work, and also adopting the ideas and methods from the studies in the computer music domain. A dimensionality reduction technique and methods of interpolating a predefined set of parameters will be introduced. The proposed methods will be compared to previous research and its use cases will be introduced as well.

Chapter 3

Methodology

3.1 Background Concepts

3.1.1 Terminology

As mentioned in the previous section, different studies use different terms for similar concepts. First of all, *parameter space* is the multi-dimensional space where each axis corresponds to independent parameters of the system. In other studies, it is also named 'phase space'. Inside the parameter space, there will be points of interest that the artist wants to use them as reference for other controls or use them directly in the control. In this research, those points will be named *reference points*. In the previous studies, similar concepts were referred to as 'desirable point', 'data point', 'parameter snapshot', or 'key state'. For continuous controls or for more detailed controls the user would want to generate a mix of the reference points. In many different cases, this process is called 'morphing', 'mapping', or 'interpolation' though they sometimes point to slightly different processes. In this research, it will be called *interpolation* since it actually will be implemented mathematically with vector interpolations. With the interpolations, the artist can create trajectories in the parameter space that the system follows while changing the value of parameters accordingly. When there are too many parameters

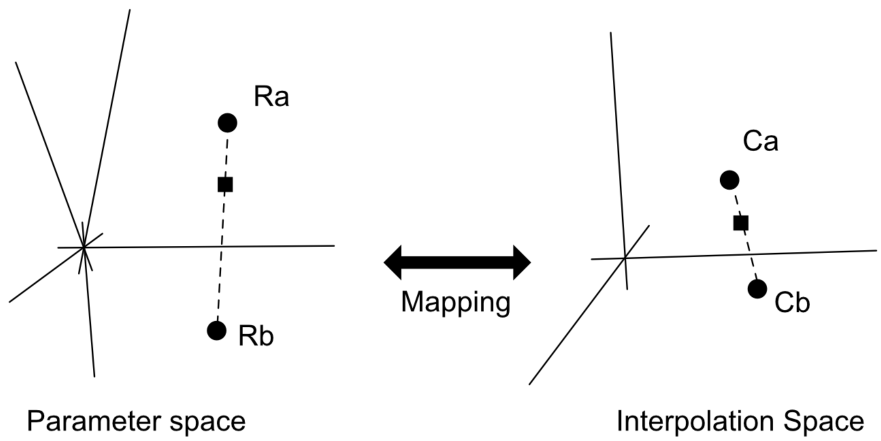


Figure 3.1: Terminology diagram. Points `Ra` and `Rb` are *reference points* in *parameter space*, and `Ca` and `Cb` are mappings of the reference points in the *interpolation space*. The *mapping* connects interpolation space and parameter space. The square points signify the interpolated point from two reference points, or from two mapped reference points in the interpolation space

involved, a dimensionality reduction can be applied to limit the degree of freedom in the control process. For the space produced by dimensionality reduction technique, *interpolation space* will be used to refer to it. Lastly, *mapping* is the connection and translation between the parameter space and the interpolation space, enabling transforms of coordinates back and forth. Figure 3.1 shows the terminology and their associated diagrams.

3.1.2 Simplex

Coxeter defines simplex as follows in chapter "Ordinary Polytopes in Higher Space" of his book "Regular Polytopes" [29]:

> "In space of no dimensions the only figure is a point, Π_0. In space of one dimension we can have any number of points ; two points bound a *line-*

segment, Π_1, which is the one-dimensional analogue of the polygon Π_2 and polyhedron Π_3. By joining Π_0 to another point, we construct Π_1. By joining Π_1 to a third point (outside its line) we construct a triangle, the simples kind of Π_2. By joining the triangle to a fourth point (outside its plane) we construct a tetrahedron, the simplest Π_3. By joining the tetrahedron to a fifth point (outside its 3-space !) we construct a pentatope, the simplest Π_4 (See Fig. 7.2A). The general case is now evident: any $n+1$ points which do not lie in an $(n-1)$-space are the vertices of an n-dimensional *simplex*, whose elements are simplexes formed by subsets of the $n+1$ points, namely the vertices themselves, $\binom{n+1}{2}$ edges, $\binom{n+1}{3}$ triangles, $\binom{n+1}{4}$ tetrahedra, ..., and finally, $n+1$ *cells*: in a single formula,

$$N_k = \binom{n+1}{k+1}$$

"

According to the definition, with `N` reference points a `N-1` simplex can be created and there will be a space of dimension `N-1` that encompasses the simplex with minimum dimension. For example, three reference points in three dimensional parameter space will from a 2 simplex and a 2 dimensional plane can be defined (spanned) from that simplex. Here the space will be referred to as a space spanned from the simplex. The plane can be thought as a subspace of the parameter space, and can be used as interpolation space for control purposes. This construction of the simplex shapes and their spanned space is the dimensionality reduction technique used in this research. When the artist defines a number a reference points, a subspace can automatically be generated and be used as interpolation space. It is natural to use this subspace as interpolation space since it

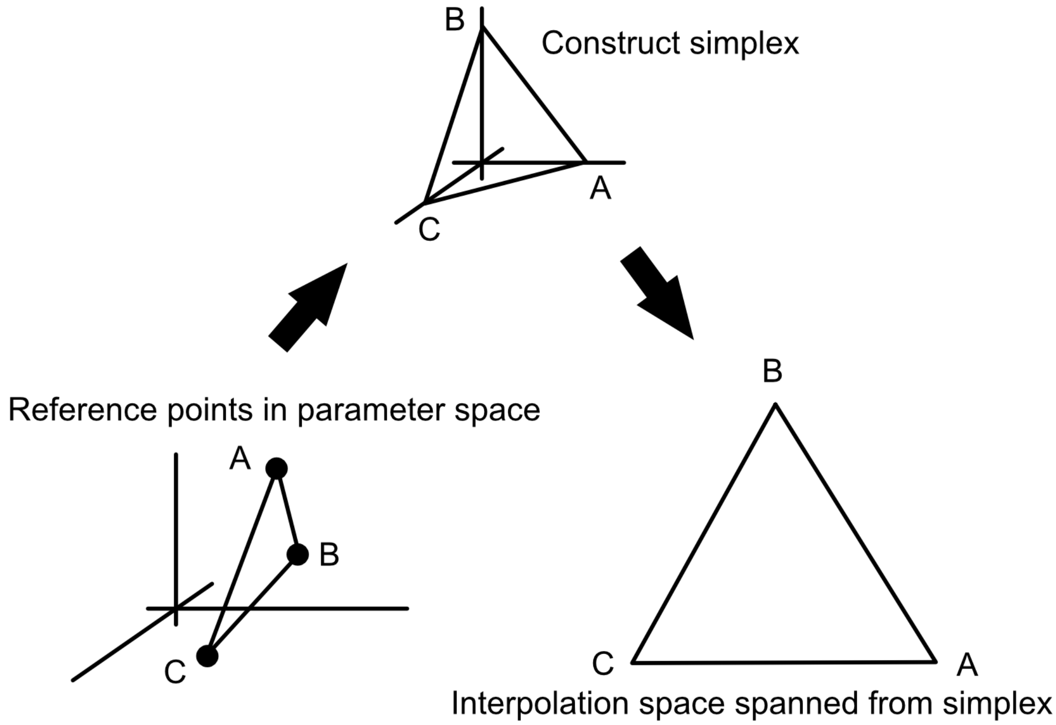


Figure 3.2: Dimensionality reduction by constructing simplex from reference points

will encompass not only all the reference points the artist defined but also all the linear interpolations of them. Again with the example above, it is trivial that any point on the interpolation space (plane) can be uniquely specified as a linear interpolation of three reference points. Also note that with this mapping regardless of the geometric relation between the reference points, the mapped simplex will provide means to think within the domain of well defined geometry. Figure 3.2 illustrates how the dimensionality reduction is performed.

3.1.3 Barycentric coordinate

Geometrically, barycentric coordinate is specified as proportional distance from mass centers on the vertices of a simplex. Again from Coxeter [30]:

> "Similarly, as Möbius observed in 1827, we may set up barycentric coordinates in the place of a triangle of reference $A_1A_2A_3$. If $t_1+t_2+t_3 \neq 0$, masses t_1, t_2, t_3 at the three vertices determine a point P (the centroid) whose coordinates are (t_1, t_2, t_3). In particular, $(1, 0, 0)$ is A_1, $(0, 1, 0)$ is A_2, $(0, 0, 1)$ is A_3, and $(0, t_2, t_3)$ is the point on A_2A_3 whose one-dimensional coordinates with respect to A_2 and A_3 are (t_2, t_3). To find coordinates for a given point P of general position, we find t_2 and t_3 from such a point Q on the line A_1P, as in Figure 13.7*b*, and then determine t_1 as the mass at A_1 that will balance a mass t_2+t_3 at Q so as to make P the centroid. Again, as in the one-dimensional case, these coordinates are homogeneous:
>
> $$(t_1, t_2, t_3) = (\mu t_1, \mu t_2, \mu t_3) \quad (\mu \neq 0).$$
>
> Joining P to A_1, A_2, A_3, we decompose $A_1A_2A_3$ into three triangles having a common vertex P. *The areas of these triangles are proportional to the barycentric coordinates of P*, as in Figure 13.7*c*. This fact follows at once from 13.42, since
>
> $$\frac{t_3}{t_2} = \frac{A_2Q}{QA_3} = \frac{A_1A_2Q}{A_1QA_3} = \frac{PA_2Q}{PQA_3} = \frac{A_1A_2Q - PA_2Q}{A_1QA_3 - PQA_3} = \frac{PA_1A_2}{PA_3A_1},$$
>
> and similarly for t_1/t_3, t_2/t_1. Positions of P outside the triangle are covered by means of our convention for the sign of the area of a directed triangle. The

inequality

$$t_1 + t_2 + t_3 \neq 0$$

enables us to normalize the coordinates so that

$$t_1 + t_2 + t_3 = 1$$

"

As noted, locating a point in the simplex can be done with the barycentric coordinate system. Since the sum of every component is 1, the coordinate can well represent the interpolation and extrapolation of vertices of the simplex, which are the reference points in parameter space. Each element of the barycentric coordinate will be connected to one of every reference points. Barycentric coordinate not only uniquely specifies points inside the simplex but also can do the same for points outside the simplex, given that the point is in the span of the simplex. Therefore when an interpolation space is given created by a number of reference points, one can locate any point in the interpolation space with the barycentric coordinate. For mapping the interpolation space to the parameter space, conversion from the barycentric coordinate of the interpolation space to the Cartesian coordinate of the parameter space is a simple weighted sum, each value of barycentric coordinate being the weight and multiplied to corresponding reference points. Figure 3.3 shows how points in the interpolation space can be located using barycentric coordinate.

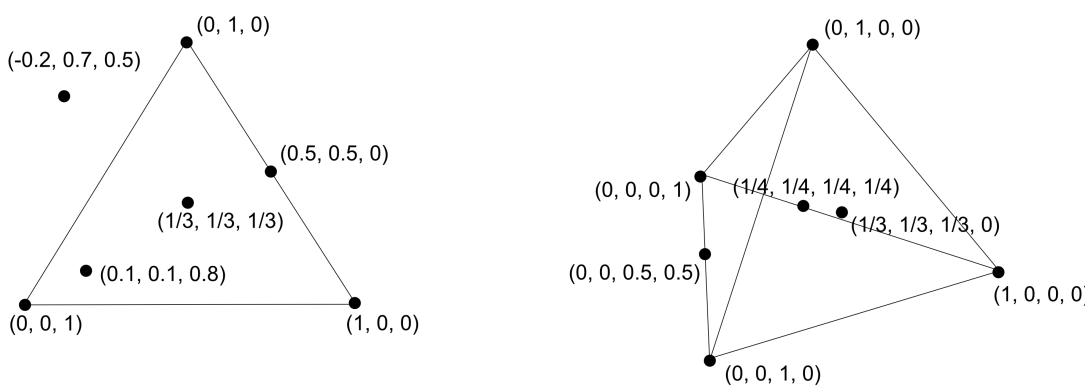


Figure 3.3: Using barycentric coordinate to locate points in interpolation space

3.2 Tools

3.2.1 Allolib

For implementing projects introduced in this research a digital media programming framework in C++ programming language *allolib* [31] is used. Along with allolib, a sound synthesis library Gamma [32] by Lance Putnam is used also. Gamma Provides comprehensive functionalities needed for digital sound synthesis. Allolib is a forked project of AlloSystem: a cross-platform suite of C++ components for building interactive multimedia tools and applications [33], developed by AlloSPhere Research Group at MAT, UCSB. AlloSystem and allolib provides c++ based interface on comprehensive range of functionalities for audio, visual, and networking in the field of media art. They also provide the warping and blending of the result image for non-planar surface projections according to projector calibration data, enabling the operation in the AlloSphere facility [20] at California NanoSystems Institute, UCSB [34]. The main advantages of the allolib compared to the AlloSystem is: 1. Adoption of higher version of OpenGL (Version 2.1 $\rightarrow$ Version 3.3), 2. Native support for Microsoft Windows Visual Studio platform, 3. More stable dependency handling, and 4. Integration with well supported Dear IMGUI library [35] for application GUI. The projects using allolib varies from scientific visualizations to immersive media artworks.

3.3 State Space

3.3.1 Existing method as starting point

In many cases, the original parameter space of a generative system has a high number of dimensions. For the compositional control process with the system, the most straightforward brute force approach would be managing parameters one by one for the duration of the artwork. While this method will give infinite possibilities and most delicate control, at the same time the enormous size of parameter space will overwhelm the artist and complicate the search of right parameter values, slowing down the creative process. As mentioned above, one approach is to treat a number of the specific combination of parameters as a reference point in the parameter space of the generative system and perform interpolations between them. This method removes the complexity that is linear to the number of independent parameters. However, this method puts the set of possible states only on the lines connecting the two reference points, and still the artist has to find individual reference points one by one. Technically this is a dimensionality reduction to 1-dimension. Unless intended it could be a limitation if the artist tries to find more possibilities in the parameter space. Also while it works well for creating a temporal structure with provided reference points, it does not assist in finding the wanted parameter values (navigation in the parameter space). This is an important point since the creative process is a two-sided activity consisting of contrasting elements: "divergent exploration and convergent optimization"[12].

As given in the section *previous research*, various approach for this problem has been studied. Common key ideas are dimensionality reduction to create an interpolation space, finding the control points in the interpolation space, and doing the interpolation between control points in the interpolation space. Then the control points in the interpolation space can be mapped to the original parameter space. In this research, the dimensional reduction will be done with the construction of the simplex geometry from reference points and the interpolation will be done inside the barycentric coordinate. After defining N reference points in the parameter space, the artist can construct $N-1$ simplex with them being the vertices of the simplex. Then the N dimensional barycentric coordinate will be able to define the locations not only the inside of the simplex but also the outside of the simplex (with negative coordinate values). This span of the barycentric coordinate represents (and can be mapped to) an $N-1$ dimensional subspace of the original parameter space. The mapping is a simple weight sum of each reference points with the weight of each being corresponding barycentric coordinates. In this manner, when the original dimension of parameter space is M, dimensionality reduction from M to N is possible, and the subspace with barycentric coordinate becomes the interpolation space created by the dimensionality reduction. Traits such as continuity and differentiability remain the same in the process of mapping in both directions.

3.3.2 Generalization of interpolation method into higher dimension

The concept of interpolation between reference points is an effective and proven method that has much research already done with many practical usages. With different interpolation functions, one can create expressive movements in both space and time. This research hence proposes an extended version of the interpolation interface, so that the rich ground of the studies on interpolation is not abandoned.

Setting up and using the proposed interface starts with observing that two reference points form 1-simplex. Just as mentioned in above paragraphs, the proposed process is, first, form a subspace of the parameter space out of the reference points: by constructing simplex geometry and spanning it to its encompassing space, and then parameterize the space with a number of independent variables with the barycentric coordinate system. When the traditional interpolation interface is explained with this process, it is a case of two reference points. It creates an interpolation space with two variables `s` and `t` with barycentric coordinate condition `s + t = 1`. These barycentric coordinates are often used as t and $1-t$ for most of the cases for weighted sum, which is how the familiar basic linear interpolation formula is written most of the time.

When this process is generalized, `N`-simplex can be formed from `N+1` reference points, subspace of $N-1$ dimension is spanned (which is the interpolation space), and then the interpolation space is parameterized with `N` barycentric variables, with condition $\sum_{i=0}^{N} x_i = 1$. For example with three reference points, a 2-simplex, triangle, is formed and with three variables `x`, `y`, `z` with condition `x + y + z = 1`. While the barycentric coordinate will have 3 variables, actually the degree of the freedom is 2 since the condition of the barycentric coordinate system eliminates one degree of freedom. So with N reference points, dimensionality reduction to $N-1$ dimension is possible.

Every interpolation techniques such as linear interpolation, ease-in/out, and/or step functions are trivially applicable to be barycentric coordinates. It becomes obvious with an example of 3 dimensional barycentric coordinates. In three dimensional space, the condition $x+y+z=1$ is a plane. The interpolation between points on the plane will be also on the plane.

Compared to arbitrarily selecting N axes to construct a lower dimensional interpolation space, the proposed method has an advantage that the existence of the reference points makes the constructed interpolation space to be more predictable. Especially for the region inside the simplex, the user can rely on the result of mapping the barycentric coordinate to the parameter space is a mix of the defined reference points. This characteristic helps in the predictability and intuitiveness when working in the interpolation space, making it easy to imagine what the result of the mapping will be.

3.3.3 State space as dimensionality reduction technique

To state again, the process of creating a simplex from a number of reference points work as a dimensionality reduction technique for the parameter space. The output is a subspace of the original space that can be defined with the barycentric coordinate. When `N` the number of reference points is larger than 2 (the trivial case, the same situation with two-point interpolation) the subspace encompasses an $N-1$ dimensional volume (instead of a line) that can be accessed with the barycentric coordinate of the space. The barycentric coordinate not only defines the points inside the simplex geometry but also defines the ones outside. From that, the subspace does not get constrained by the boundary of the simplex geometry and spans infinitely out to the dimension it is in, which is the interpolation space.

For the proposed interpolation space this research proposes the name “state space”, in the context that it defines the region the state of the generative system would occur in the control process. Also, the entire workflow of the creative process using state space will be mentioned as ‘using state space interface’. Every point in the state space represents a mixture of reference points in the parameter space, and the barycentric coordinate values of the points are the mixture weight for each reference point. Also Regardless of geometric relation between the reference points, the barycentric coordinate makes it possible to regard the simplex created as a regular simplex, just like figure 3.5.

3.3.4 Advantages

There are many advantages to the state space interface. First of all, it is not tied to a certain dimensionality. It can be used for any dimensionality of parameter space while constructing state space with any dimensionality for the artist’s needs. Also after constructing a state space with a certain dimension, it is trivial to add any number of

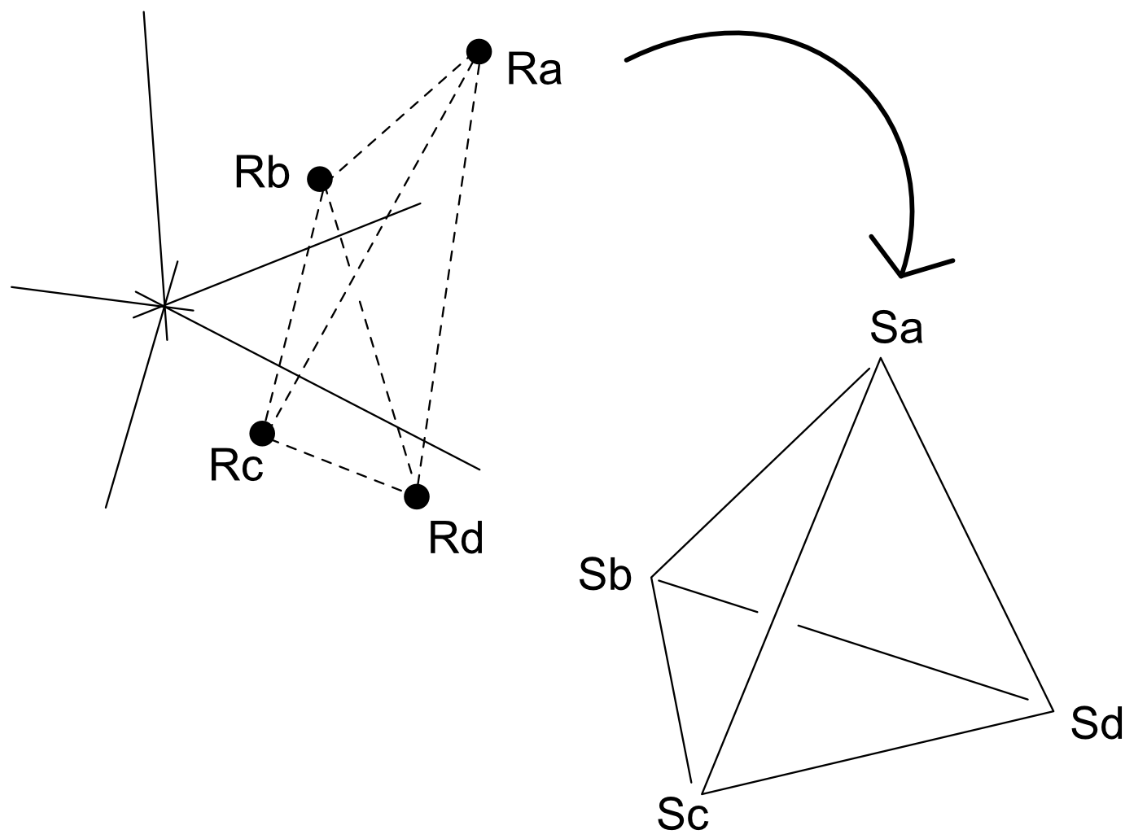


Figure 3.4: State space with simplex geometry and barycentric coordinate

dimensions. For example, when there is a key point with three dimensional barycentric coordinate $(0.5, 0.3, 0.2)$, the user can add a reference point in parameter space while also adding 0.0 to the end of the key point coordinate. It will give $0.5, 0.3, 0.2, 0.0)$ which represents the same point as before but now belonging to the new state space.

The calculation is light and simple in terms of both complexity and performance. There is no need for setup calculation or preparation calculation. Also when running the interface, there is no edge case and there are no conditional calculations. Just a simple and fast weighted sum is used to map the control points to the parameter space.

The state space interface is an embracing scheme that does not abandon the previous techniques. All the interpolation related techniques and linear operations can still be used

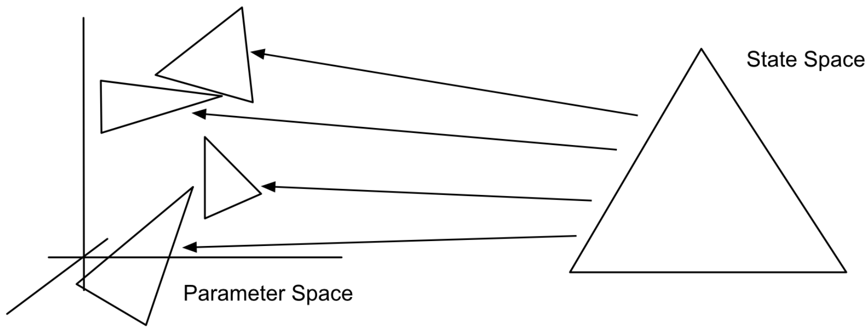


Figure 3.5: Any combination and selection of reference points will be mapped to a regular simplex

without any adjustments. This is because while the barycentric coordinate seems like a separate system, the coordinates actually are the set of subspace for cartesian coordinate based space. For example, the state space spanned from 2 simplex triangle is a planar subspace inside the 3-dimensional cartesian space. all the barycentric coordinates are just a specific set of points that lie in the cartesian coordinate system. Hence all the interpolations and linear operation between them can be used freely and natively.

The last advantage of the state space interface is that every reference point is treated the same by other reference points. In the parameter space, depending on their geometric relations, certain reference points can be nearer to each other than other points. This results in the need for extra care when interpolating them. For example, when the distance between reference points are different, the velocity (rate of change) of parameters is hard to manage when using simple interpolations in the parameter space.

These are the technological advantages of the state space. The next sections introduce more characteristics of the state space interface, in the context of the user experience side.

3.3.5 Abstraction of system state

Now given a state space formed by a number of reference points, the artist can pick the desired point in it with ease by using the coordinates. Since the sum of the coordinates is 1, it is just as intuitive as selecting the portion of each ingredient for a mixture. For example, when there are three reference points A, B, and C, coordinate `(0.3, 0.2, 0.5)` will represent a state that is 30% A, 20% B, and 50% C. These points in the barycentric coordinate will be named as "key points", similar to the term keyframe in the field of animation, and their barycentric coordinate value will be called 'control coordinate'. Later key points in the state space can be easily mapped to the parameter space by weighted sum formula. Key points not only enables the blending of reference states but also provides an abstraction over the parameter values.

Note that the barycentric coordinate is dimensionless. No matter what parameter value it represents (or it will be mapped to) they are all in the well-defined range: $(1, 0, 0)$ is mapped to the first reference point, $(0, 1, 0)$ to second, etc. Even if one of the parameters of the system is in the scale of 10^2 and another is in 10^4, they would still be well interpolated regardless of their units when handled within the state space. Furthermore, since the coordinate is also decoupled from the reference points, even when the reference points are changed the representative character of key points will remain the same, as figure 3.6 demonstrates. That is, whatever reference point was used, control coordinate $(0.5, 0.5, 0)$ will always represent 50:50:0 mix of current reference points. Also, changes to parameter values of reference points will automatically update the key points. This feature is useful when the artist wants to adjust the entire key points in a certain direction. Figure 3.6 also illustrates this scenario. While the reference point C in the parameter space is moved, the key point denoted by black square maintains its abstraction: being a mix of reference point A, B, and C with the ratio of 2:2:6.

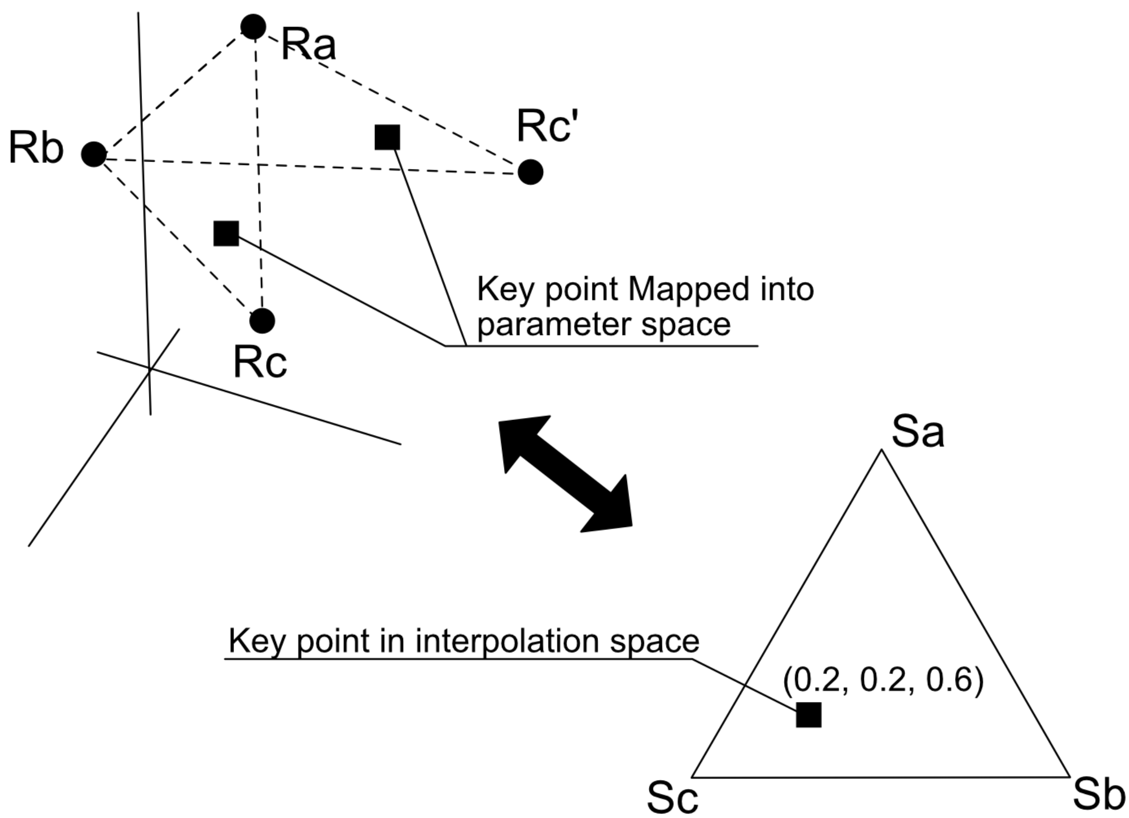


Figure 3.6: The barycentric coordinate abstractions remain the same while adjusting different part of the state space interface

3.3.6 Separating the control structure from parameters

When thought with the trajectory of a system in mind, this brings interesting possibilities for the temporal control structure. When the artist design a motion that is defined with barycentric coordinate inside the state space (figure 3.7), without need to revise or fix the motion, the artist can adjust, switch, or swap the reference points to produce new motions with same temporal structure as the original one. Those motions will have the same higher-level structure but have different lower-level details since the actual value of parameters are different. Then the motion even can be applied to a different generative system, which suggests the capability of reusing the temporal structure

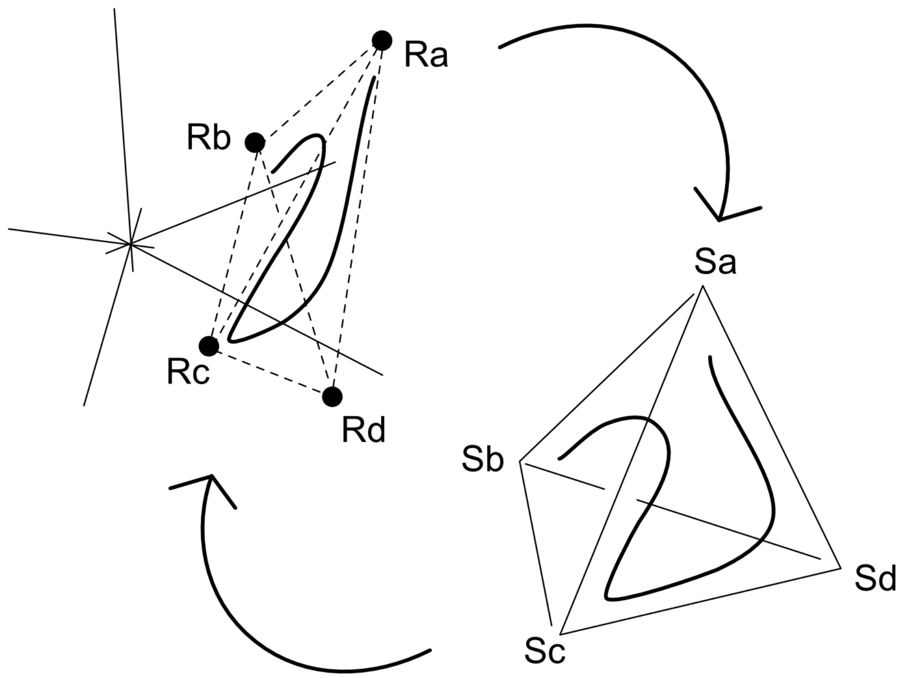


Figure 3.7: Design of motion in state space and its mapping to the parameter space

for different artworks. This is essentially a separation of the temporal structure from material detail (the system parameters). This separation enables working on the large higher scale structure with the lower level details decoupled. Figure 3.8 shows one kind of motion being applied to different sets of the reference points.

3.3.7 Example workflow scenario

Summarizing the introduction to state space, the following is a proposed workflow scenario where an artist uses the state space interface for a generative system. Here it is assumed that the generative system has ten parameters and the artist chose to use three reference points (10 is arbitrary, and 3 is for ease of illustration), and the artist will be referred to as 'he'. The example will show illustrations without showing a GUI based workflow, but note that attaching a GUI or not is a selective and can be easily done with

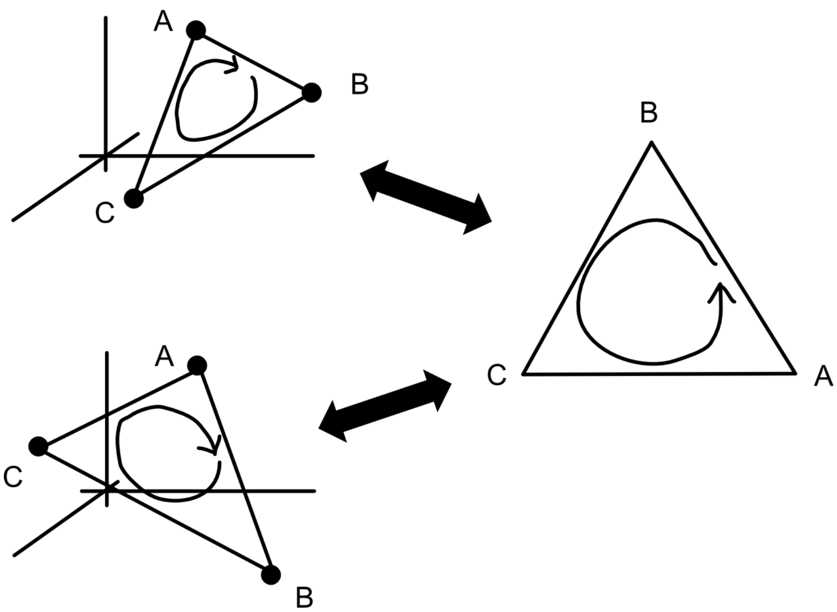


Figure 3.8: switching reference points while using same motion in the state space

value sliders or similar widgets.

First, he will choose three reference points to start with, each having approximate values he is thinking about. Now he can go through the navigation process within the state space spanned by three reference points with 3D barycentric coordinate: figure 3.4. From here, he can sample different points in the state space for creating key points, or adjust the parameter values of the reference points to modify the whole state space. When adjusting parameter values, not only he can manipulate ten parameters, he can also use control coordinate to find a new candidate quickly. This is an iterative process, but the dimensionality reduction from state space makes the process more effective, efficient, intuitive, and user-friendly. Just as mentioned above in the general explanation, the already found key points will automatically update as the artist adjusts the reference points. This is the divergent exploration done with state space interface.

After finding good enough reference points can key points, the artist can start designing a temporal structure through creating motions in the state space by sequencing, connecting, or transforming the key points: the convergent optimization. When designing temporal motions with key points the artist can use all the traditional interpolation techniques to interpolate between the key points. All the vector-based approach still applies to the barycentric coordinates. For example, multiple points can be connected with parametric splines such as Catmull-Rom splines and then interpolated to smoothly animate motion in the parameter space. Another possibility is to define a parametric motion to move points in time automatically. This is an analytic approach with the potential for complex motions in the state space. A simple case would be a circular movement in the two-dimensional plane generating a modulating motion in the state space. Spontaneous spawning of points from probability can be interesting too. With predefined tendency, points can be generated in the simplex to create a cloud of instances of the generative system. One can imagine techniques such as granular audio synthesis to be used with this kind of pattern. Polyphonic control is also possible by controlling multiple key points in the state space. Figure 3.9 shows diagrams for mentioned patterns. These patterns are not the only ones that the user can apply. The state space does not limit the boundary of techniques but only facilitates the part of dealing with the parameter values.

Also, At some point at the artwork's temporal span, the artist might want to give a change to the overall tone of the work, while maintaining the local temporal structure. This can be done by switching or transforming the reference points while maintaining the motions used (figure 3.10). This effect comes from the fact that change in the reference points is the change in the interpolations space, which is the subspace where all the mapped key points will belong to. Since the motions based on barycentric coordinate is decoupled from where in the parameter space the reference points are, there is no need for the artist to update the motions. The motion of the reference points directly affects the

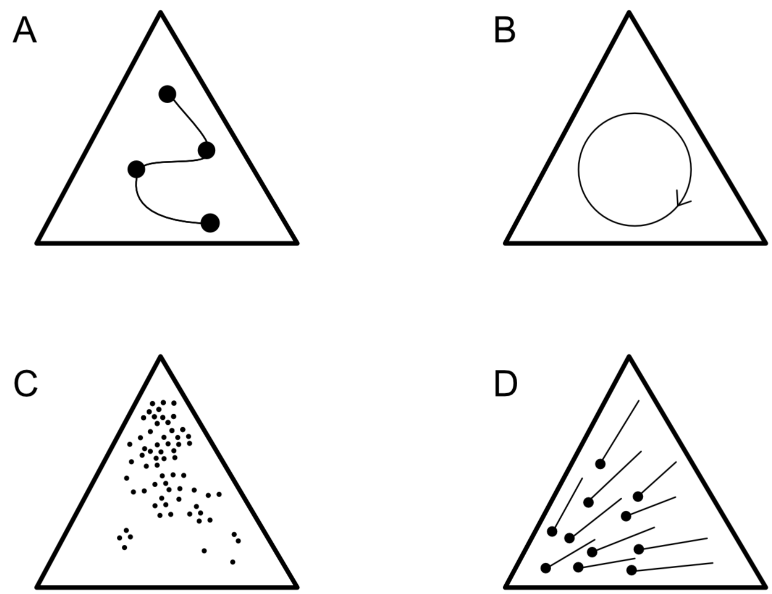


Figure 3.9: A: Connecting key points with spline, B: Having an analytic motion, C: Spontaneous spawns of key points, D: Polyphonic control with each key point having its own motion

overall motion. When the reference point is smoothly moved in the parameter space, a smooth change in the interpolation space is performed. The rapid change in the reference points or even the switching of them will result in sudden motion in the overall outcome of the generative system.

So far, the technical aspect of utilizing the state space interface was discussed. The state space interface facilitates the search of the right parameters and enables the efficient construction of the temporal structure. These advantages come from the separation or decoupling of the control coordinate (key points in barycentric coordinates of the state space) from the actual values of the parameters (reference points in the parameter space). In the next section, state space interface in the context of temporal composition will be discussed.

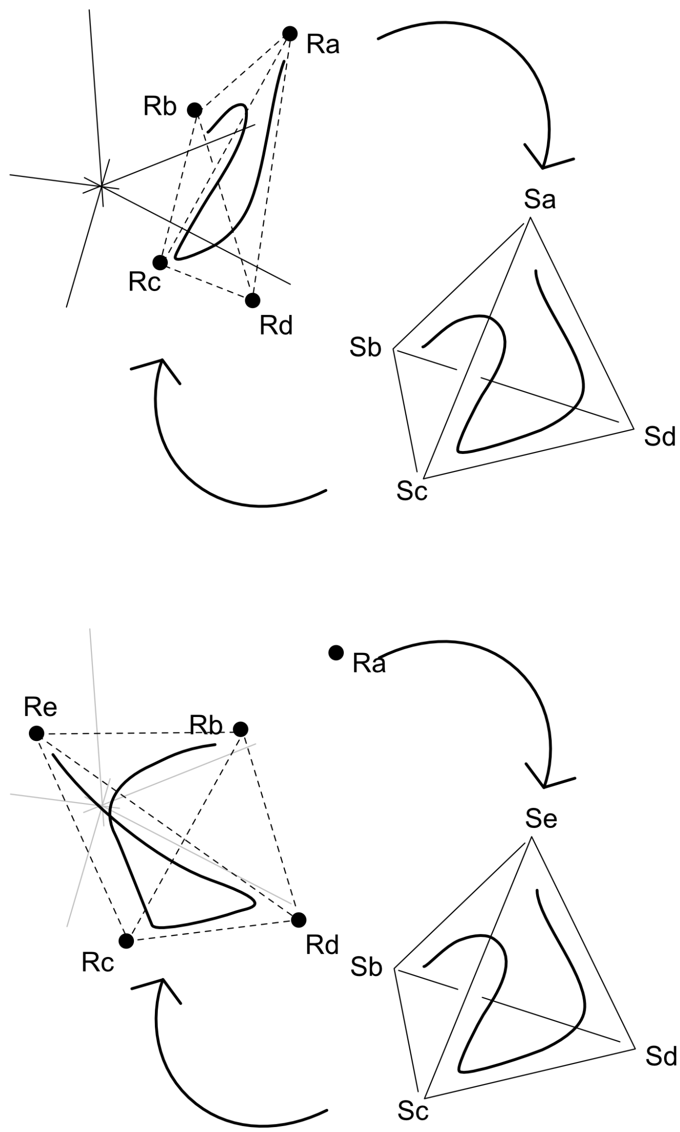


Figure 3.10: Switching reference points for different presentation. Reference point A (top) is switched with E (bottom). Note that the motion in state space remains the same and gets automatically mapped

3.4 State Space as Compositional Interface

3.4.1 Foreground, middleground, and background

The creative process of interest in this research brings together the emergence of the generative system and temporal structure for manual control. By designing the generative system, the artist sets up a potential of emergence. Then with the manual control over the system, the artist can maximize the presentation effect of the system. As mentioned in the introduction, the generative system better creates smaller-scale motions and details ("formal methods works best at the lower levels, for material and structure generation." [8]) while the manual control can form larger-scale movements and structures just as traditional composers have shown. In traditional compositional terms, this combination can be thought of as the generative system handling the foreground while the manual control handles the background of the work. The middleground is an ambiguous area, depending on the specific artwork. If the generative system takes charge of a big portion of the control, the middleground will be also included in the generative part. If more manual control is done for the work, middleground will belong to the manual control domain. To summarize, the artist prepares materials to fill the foreground when implementing the generative system and structures the composition while manually designing the temporal control.

This situation of a generative system with explicit control is similar to a shepherd dog guiding herd of sheep. While the dog does not control the individual motion of each and every sheep, it controls overall large scale movement direction of the herd by giving inputs to the herd barking or running towards a certain direction. The individual motion of sheep is governed by their internal rule of flocking. This natural flocking is one of the great examples of the generative system, that has inspired artists to come up with a simplified version of it [36]. Hence the generative flocking system is controlled by the manual, or canine, input to achieve a specific goal. The result of generative detail and manual control mixed together is a mesmerizing scene of sheep herd flowing and swirling. If there was no dog (no manual control) the sheep would still flock but in any random direction. If the sheep directly responded to the dog's control (no generative system), the herd would just move in uniform motions, parallel to each other. This example is tightly related to the main motivation and question of this research: without a certain degree of manual control, the generative system has a high chance of being lost in the uninteresting region.

By combining the generative emergence and temporal structure controlled manually, the artist can pursue more significant potential in the aesthetic quality of the artwork. This is how the idea of foreground, middleground, and background from the traditional composition can be brought to modern generative artworks. Thinking in these layers of different scale help the artist plan and structure how the work should unfold in time. Using state space interface dramatically helps in this process. Since the state space model enables the decoupling of the generative system and manual control, the artist can focus on each layer individually. When working on foreground with the generative system, there is no need to worry about adjusting temporal control design since the control plan will automatically update according to the system. That is, when the generative system or the reference points are modified to change the behavior of the system in detail, the larger-scale structures made with key points in the state space do not require any kind of adjustments. On the other side, when working on the background, there is no need to consider the parameters of the generative system since the abstraction from the use of state space will manage the conversion of the parameters. With these characteristics, the state space model provides a better opportunity for artists in revealing the emergent behavior of their system.

3.4.2 Constraints as compositional element

When state space is constructed, only a certain portion (or slice) of the whole parameter space is mapped to it during the dimensionality reduction process. This could be considered as a limitation. However, carving out an unnecessary part of parameter space is the typical process of composition. By constraining the region where the state of the generative system can exist, the artist is selecting the material set, or region, for the composition. This idea of constrained space well aligns with the traditional composition method where the composer selects a certain set of materials out of many candidates and work with them throughout the work. The exclusion of unwanted material(s) is one of the effective ways to refine the design of the work. On the other side, navigation inside the state space can relate to working inside the material set. Changing, switching, or substituting the state space is similar to the transition of material set within the temporal progress of the artwork. By this process of adjusting the reference points, the artist can test and select which region of the parameter space to include or to exclude. The constraining of parameter space also prevents the system from going to the unwanted region: system states that present any interesting behavior at all, or states that go inadequately extreme to be well presented (performance issues, human perception issues, etc.). In the following section, an example of using constrained subspace for the temporal structure will be discussed with proof of concept practices.

3.4.3 Temporal structures made with state space

Continuity and contrast are the basic building blocks of a temporal structure. In this section, how to achieve those movements will be discussed. The movements can be designed in two different levels, key point level, and reference point level. In the key point level, continuous motions can be achieved by smoothly moving the control coordinate along a trajectory. The trajectory can be a line connecting two key points, or a curved spline connecting three or more points. This will make a smooth transition for the system. Depending on the speed of transition, the artist can also create discontinuity or rapid, sudden motion, for a notion of contrast. Simple jumps between the key points easily create contrast movements also. The motions such as those introduced which figure 3.9 or any other methods to create key point level motions are not excluded here and can be freely used in demand. While these movements lie inside the state space constructed by the reference points, they directly control the generative system by being mapped to the original parameter space. This position puts the role of key point level motions near the middleground of the composition. While being right above the detail generated by the system, the middleground structure conforms to the larger-scale structure defined by the state space constructed with the reference points.

The manual control can be done at the reference point level also. Continuous motion is achieved by moving the reference point smoothly in parameter space. it can be interpolated towards other reference points, or follow certain trajectory functions defined in parameter space. This method is the same as using the existing interpolation method in parameter space. During these transitions, the key points will automatically be updated as the coordinate of the reference points change in the parameter space. On the other side, an interesting motion of contrast can be achieved by switching of the reference points. It is similar to the change of key in terms of musical composition. By maintaining the state space motion but switching the reference point(s), the motion pattern is preserved while the tone, characteristic, or atmosphere is changed. While the motion in key point level could be considered as a middleground component, the change in the reference point level could be thought of as a background composition. Since the reference points define the boundary of the system state by constructing the state space, controlling the reference points is the process of deciding the largest scale structure of the work.

3.4.4 Summary

In this chapter the proposed interface: State Space Interface was introduced and discussed. First, the background concepts and terminology were covered, and then the technical methods to set up the state space interface was explained. The following were the various methods to utilize the interface. After, the implication of state space in terms of the compositional process was discussed. The following chapter introduces three works that utilize the state space interface, and also brings more discussion in depth.

Chapter 4

Practices

In this chapter the works utilizing the state space is introduced. Each artwork have their own generative system, and the generative systems are connected to compositional controls via state space interface. The *Reconstruction* is the first work to test the state space interface, showing how the state space interface can be used to create temporal control for an installation work that demands an looping composition rather than a fixed length one. The composition of the *Reconstruction* was not manually written but was automatically generated. Hence the *Reconstruction* was rather a proof of concept for the technical part of this research. The *Balanced Movement* actually brings in the motivatio nand question of the research. The manually composed sequence of control signal is connected to the stochastic system of the work via the state space interface. *Balanced Movement* shows how a manual composition can work with a generative system while preserving the autonomy of the generative system. The *Frontline* goes further by experimenting the integration of the state space interface with a realtime performance control. Just as the studies in the computer music domain use parameter control methods for intrument interface, the state space also can be used to faciliate the realtime performance control of the generative artwork.

4.1 *Reconstruction*

Reconstruction is an audio-visual installation with a 2-channel sound and a wall projection. This work presents a reconstruction of a virtual geographical object, using an observation data of a real object as input. The intent is to experiment with how the characteristic features of the original real object can be reconstructed in the virtual one. The given observation data is the digital image of the Grand Canyon. The input image is first turned into a frequency spectrum with FFT. The spectrum is then modified to pick up certain characteristics from it. Then with the modified spectrum, the generative system outputs a 3-dimensional polygon (mesh) data of a reconstructed virtual canyon. The mesh is rendered with different rendering styles depending on the compositional intent, and the audio system will output different timbre sounds to match the visual rendering style.

The work was presented at MAT EoYS 2018 [37]. Since the work is an installation, a choice was needed between repeating a fixed composition and running an endless loop. For this work, the method of looping was chosen, but the loop was designed to be not entirely random but to contain a certain amount of predefined elements. As a result, the work could be running throughout the show, without stopping, while presenting different versions of composition which are the random deviations of designed composition. The compositional process will further be discussed in the following section.

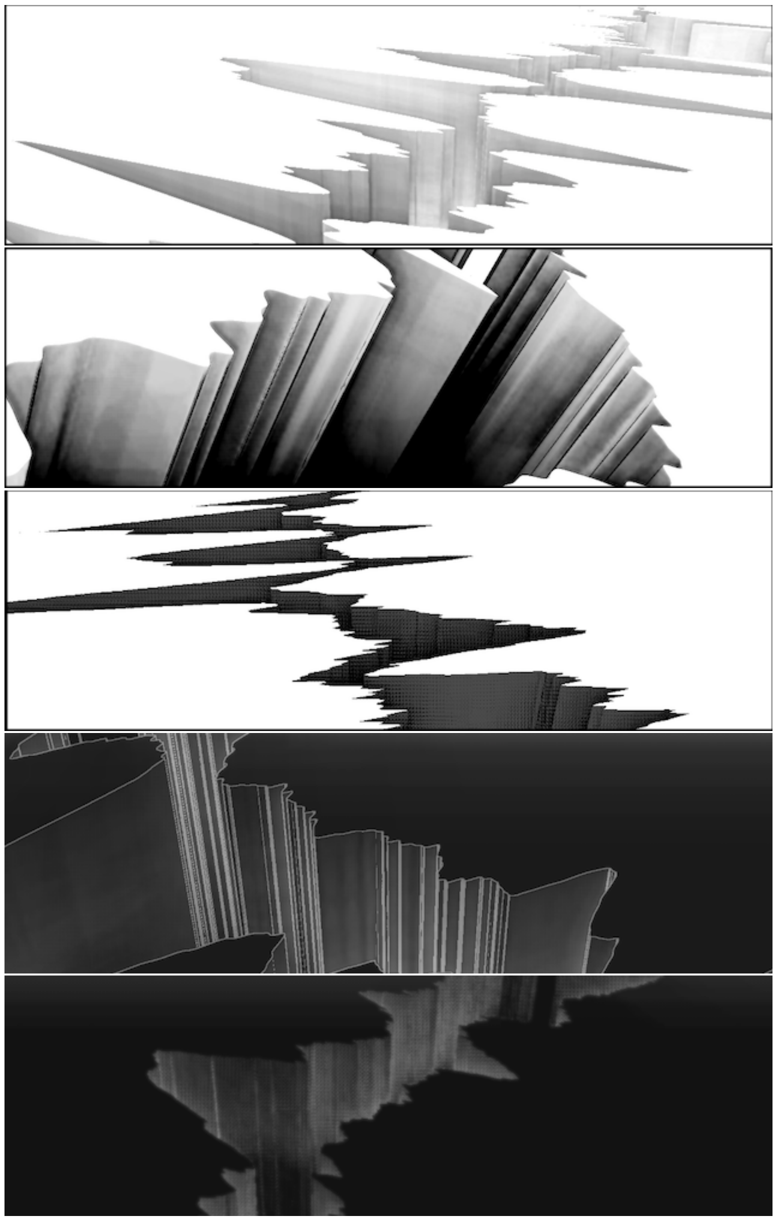


Figure 4.1: Reconstruction, 2018

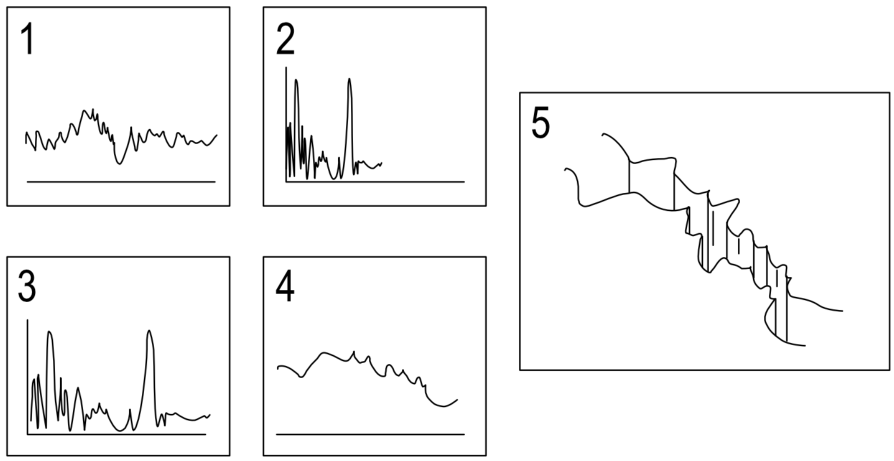


Figure 4.2: Mesh generation in Reconstruction

4.1.1 Generative system

This section covers the generative system of the work. The generative system of the *Reconstruction* takes a static digital image as input and outputs a 3D mesh of virtual canyon. The mesh generation function takes the frequency spectrum as input and returns a virtual canyon as output. The function mostly focuses on re-interpretation of the spectrum into other dimensions, units, or parameters, while also taking consideration of the fractal-like nature of geographic geometries. The input spectrum to be given to the mesh generation function is obtained from the FFT on the input image. In a simple description, the procedure consists of calculating the spectrum with FFT of the input image data, modification of the spectrum according to the parameters, and IFFT of the modified spectrum to produce output mesh.

The input spectrum is obtained from the digital image of the Grand Canyon. The

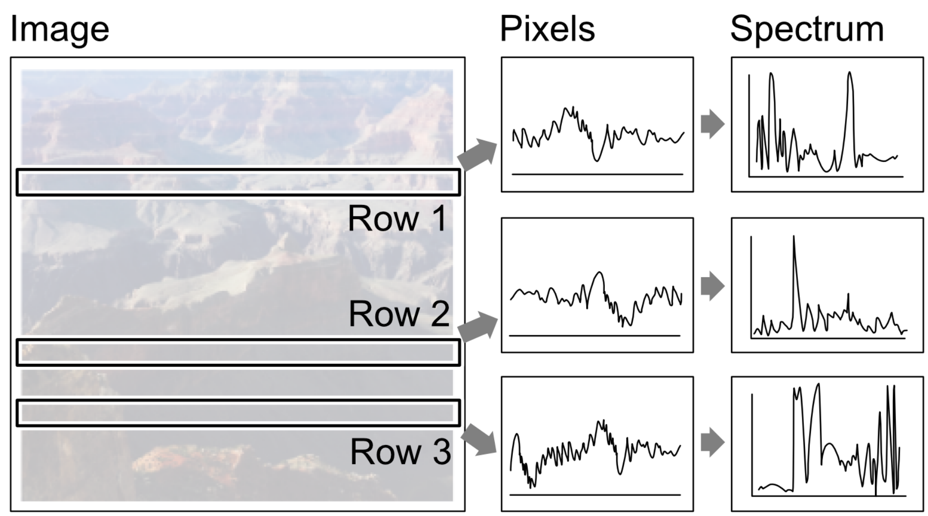


Figure 4.3: Calculation of spectrum

image was turned into single channel luminance image, which highlights the brightness patterns of the image, rather than its colors. Then the image is rescaled to 512 pixels by 512 pixels to make the output of FFT be in known size. One row (512 pixels) was used as the unit of input for FFT so that by selecting different row from the image, different result would come out. Selecting which row to process is part of the compositional process, enabling the change and motion for the scene over time. Given a row of pixels, FFT spectrum can be calculated and then the spectrum is sent to the modification process.

Now that the spectrum is calculated, it goes through the modification process. The idea of modification is to change the spectrum of luminance to the spectrum of a curve. Then the spectrum of the curve can be passed to IFFT to output actual curve data. The generated curve defines the path of the virtual canyon to be generated. In the spectrum modification process, one of the most critical parameters is the base and maximum frequency of the resulting shape. Since the FFT spectrum of 512 pixels will contain a value range of 1 to 256, mapping this value to different frequency range will significantly affect the resulting shape. While the frequency value is linearly mapped to a different range, the relative amplitude and phase information between each frequency is preserved, maintaining the unique character of the spectrum. Figure 4.4 shows the different results obtained from different frequency range mappings. Another critical parameter is the fractal dimension parameter that controls the detail of the shape: lower value will give smooth lines, while higher values enable superposition of different frequency levels hence giving noisy or organic outlines. The fractal parameters include the number of superpositions, frequency multiplication factor, and amplitude multiplication factor. Figure 4.5 shows how the details of the result mesh changes depending on the fractal parameters.

The generated shape is graphically presented with several different rendering styles and different camera positions. Rendering parameters include the blurriness, shading texture (smooth or dithered), outline stroke, and color palette (dark or light). The shading texture is calculated with an ambient occlusion algorithm. By changing the mix amount of the ambient occlusion texture, the result can vary from flat coloring to shaded rendering. Also, by changing the filtering amount of the algorithm, blurriness can be controlled. The rendering style is intended to match the mesh being shown. When presenting a smoother mesh, the visual style should use a dark blurry visual with smoother textures. A mesh with a lot of change and details will be presented with a granular texture and hard outlines. The matching of the mesh and visual style is done in the compositional stage. This matching is also done with the audio. As a whole, the three decisions: selecting the shape of the mesh by selecting the row in the image to process, selecting the visual style, and selecting the audio texture is the part of the compositional decision.

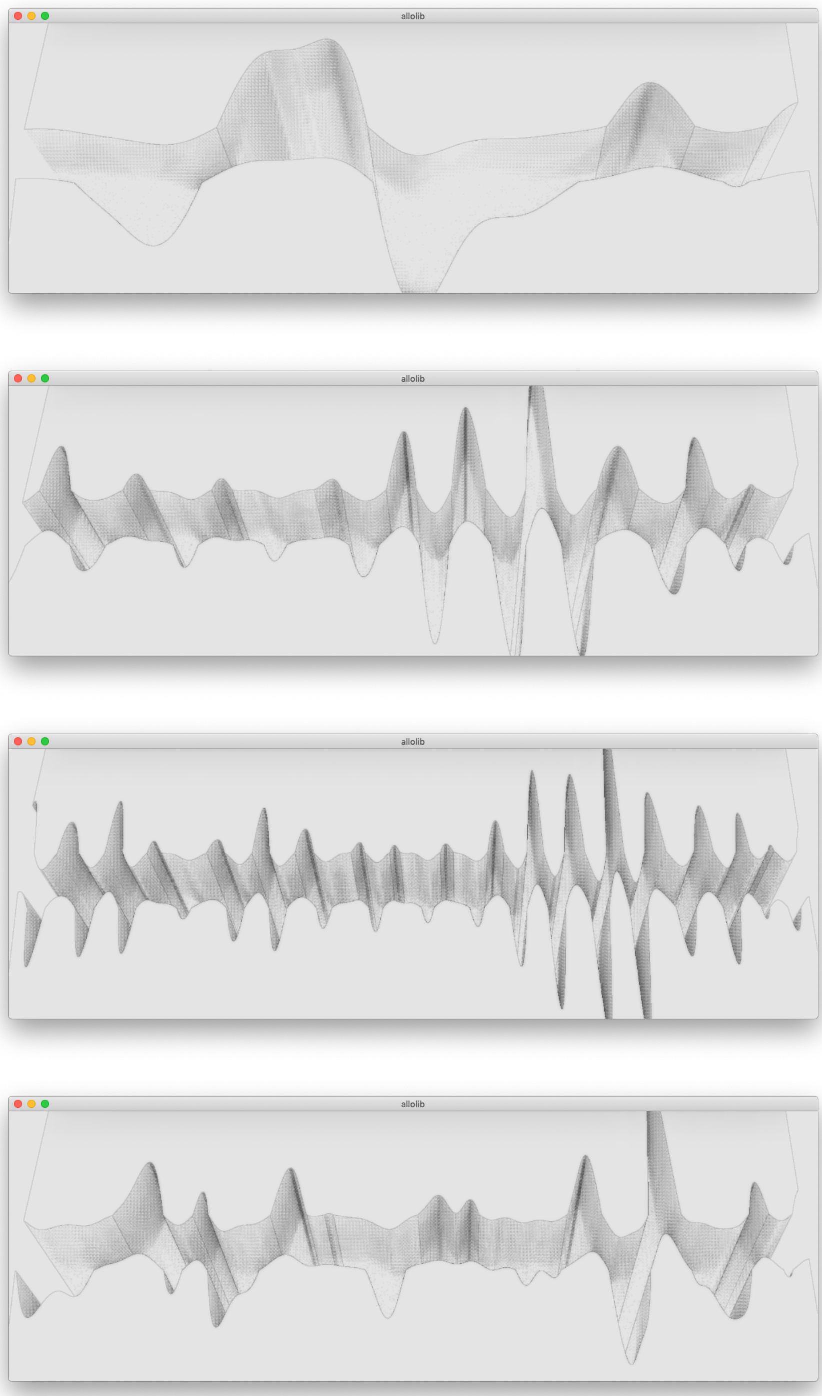


Figure 4.4: Result of different frequency range — downwards from top [1:8], [8:20], [16:32], [4:26]

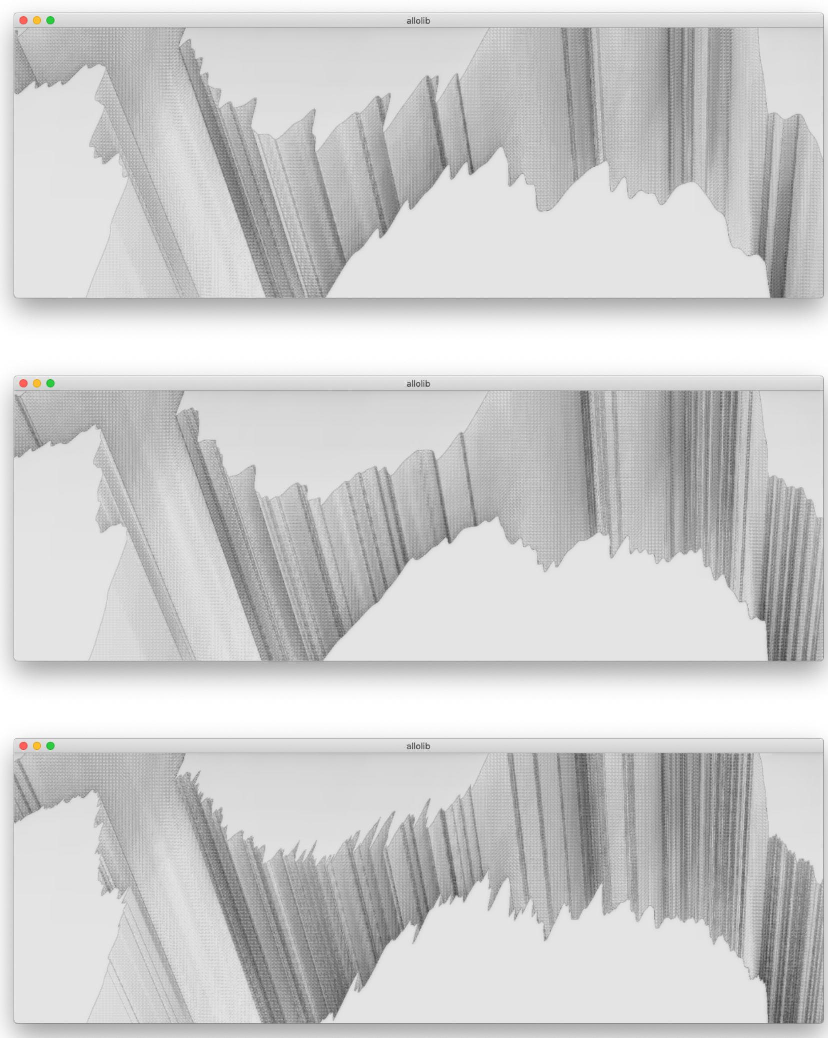


Figure 4.5: Result of different fractal levels — downwards from top 1, 2, 4

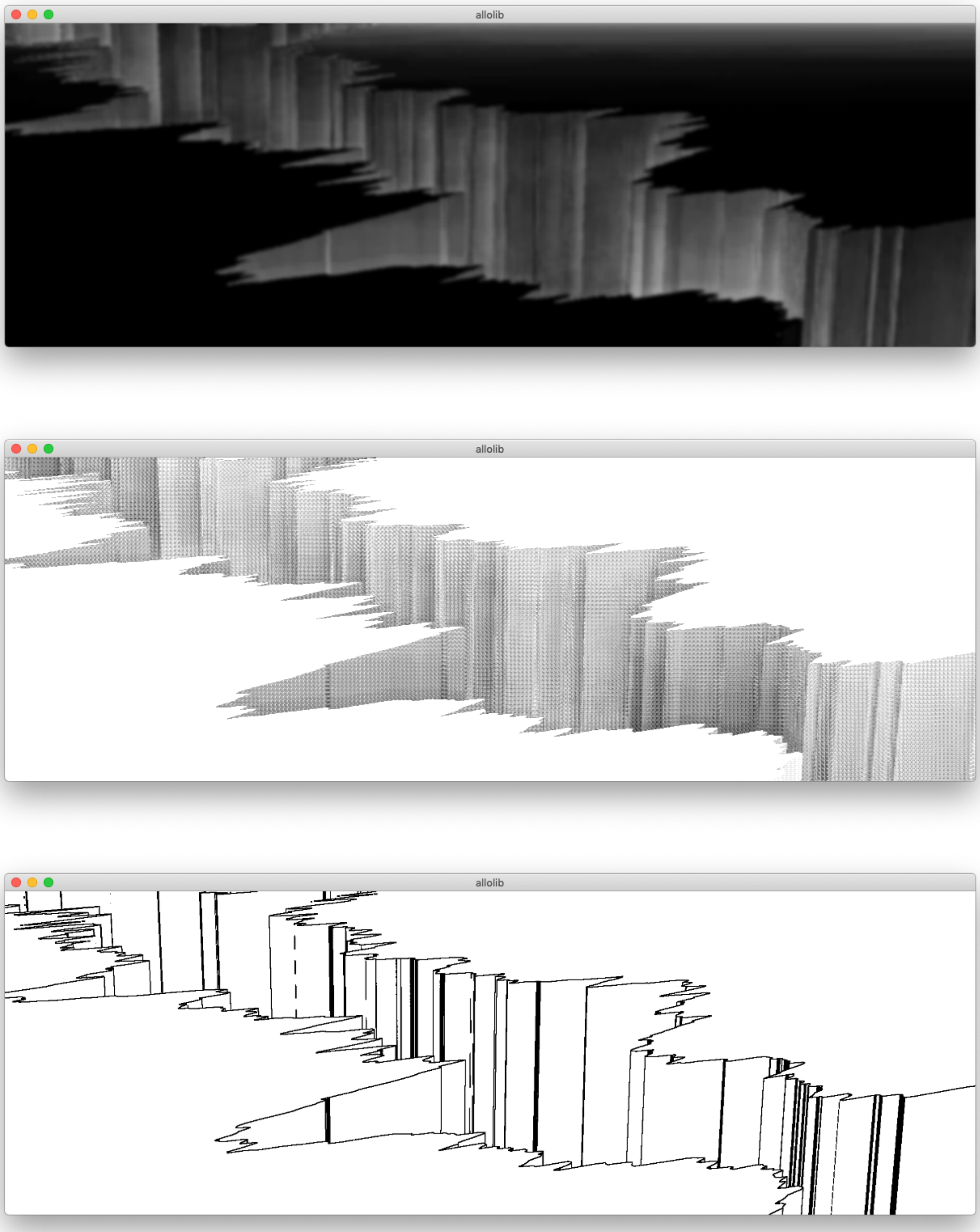


Figure 4.6: Different rendering styles

In the audio domain, an FM instrument is used while its parameters are controlled in time according to the rendering style being used at the moment. The FM instrument has a vibrato on the carrier frequency, and three chorus filters are applied after the FM process. For audio control, along with typical FM parameters such as modulation index and CM ratio, vibrato frequency, and amplitude, as well as chorus filter parameters (feedback, feedforward) are used. Depending on the parameter values the instrument gives a distinct audio texture. Figure 4.8 shows three different setups for the parameters, each setup having name FM1, FM2, and FM3. FM1 has slow attack and decay, with a large amount of feedback and feedforward terms. FM1 also has a large modulation index value. These parameters result in a smooth resonating texture, and composition will be connected with low fundamental frequency to produce a dark and blurry feeling. FM2 has low feeding terms and low modulation index but has large vibrato value, with a short attack and decay times. FM2 gives cleaner pitch sound with echo-like follow-ups. FM3 has a very short duration with a high vibrato frequency. Along with fast attack and high feeding values, it provides a dry sound that echos. The trigger frequency of the instruments is calculated from the corresponding state. When the corresponding state is in dominance, the instrument is more frequently triggered. By this mapping, the sound texture follows the generative system.

4.1.2 Composition

Inside the 10-dimensional parameter space of the generative system, three reference states of the generative system are defined: 'Silent', 'Resonant', and 'Noisy', and forms the state space of the composition. Their names represent the abstract quality of visual and audio each state generates. As the name suggests, 'Silent' presents a quiet and calm state, in terms of both audio and visual. For audio, low-frequency smooth sound

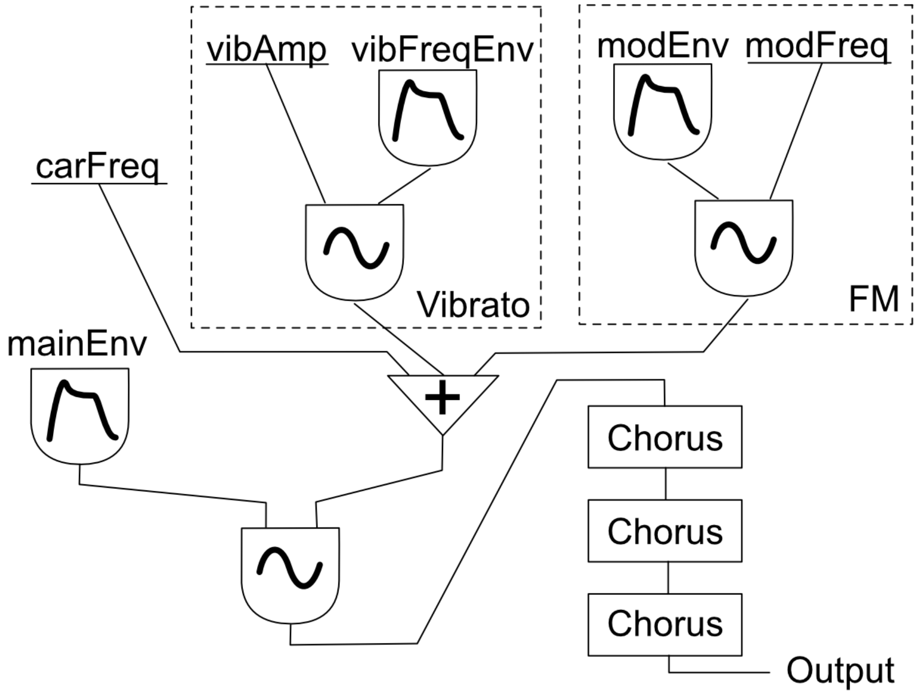


Figure 4.7: Audio instrument diagram

is triggered in a long interval with instrument FM1. For visual, a dark and blurry scene is captured from a long-distance camera shot. The 'Silent' will be the resting state of the work, used for pauses and blanks. The state 'Resonant' brings pitched sound with FM2 and float color with outlines. The state is intended to be a place where natural unfolding is happening. The 'Noisy' works as an irregular unstable state, with coarse dithered shading texture and short inharmonic sounds from FM3.

The state space formed from these reference points constrains the parameters to a plane in the parameter space, enabling control of all the parameters with three coordinate values. The constraint also prevents the system from having unintended extreme parameter values or uninteresting dull states, in terms of scale, resolution, rate of change, etc. With the constructed state space interface, the control signal can be made by sequencing the three numbers (the barycentric coordinates).

	FM1	FM2	FM3	note
trigger period (sec)	4 - 12	2 - 8	1 - 30	parameterized
base frequency	60 - 240	320 - 1280	100 - 400	randomized
amplitude	0.5 - 1.0	0.5 - 1.0	0.5 - 1.0	randomized
duration (sec)	2 - 5	1 - 3	1 - 6	randomized
attack time (sec)	0.1	0.05	0.008	fixed
decay time (sec)	1.0	0.5	0.18	fixed
vibrato multiplier	0.0075	0.02	0.054	fixed
vibrato frequency	3.5	5.8	11.3	fixed
modulator multiplier	1.0007	0.85	1.15	fixed
modulation index	7.0	1.7	3.28	fixed
feedforward	-0.7	0.0	-0.74	fixed
feedback	0.9	0.4	0.53	fixed

Figure 4.8: Parameters of three instruments

The compositional intention of the work is to provide pulses moving between 'Silent' and 'Resonant', while 'Noisy' as a contrasting element gets introduced from time to time. The loop begins in 'Silent'. Then different movements in time are generated from splines or straight lines connecting partially randomized key points inside the state space. Splines of the temporal control are implemented with centripetal Catmull-Rom spline. The centripetal Catmull-Rom spline generation method is designed to remove loops or twists in the result, giving more intuitive shapes. The 'Silent' has a tendency to go to the 'Resonant' at the largest chance, and the 'Resonant' has a similar chance of going to 'Silent' and staying at 'Resonant' itself. Both 'Silent' and 'Resonant' has a low chance of going to 'Noisy', and 'Noisy' will quickly return to the other two states. All these tendencies are defined by the probability matrix defined by the artist. By changing the matrix different compositional unfolding can be presented. The matrix will have a stationary point that the state transitions will head to, just as figure 4.10 shows. To make the path non-trivial, the composition generation process will give random deviations to

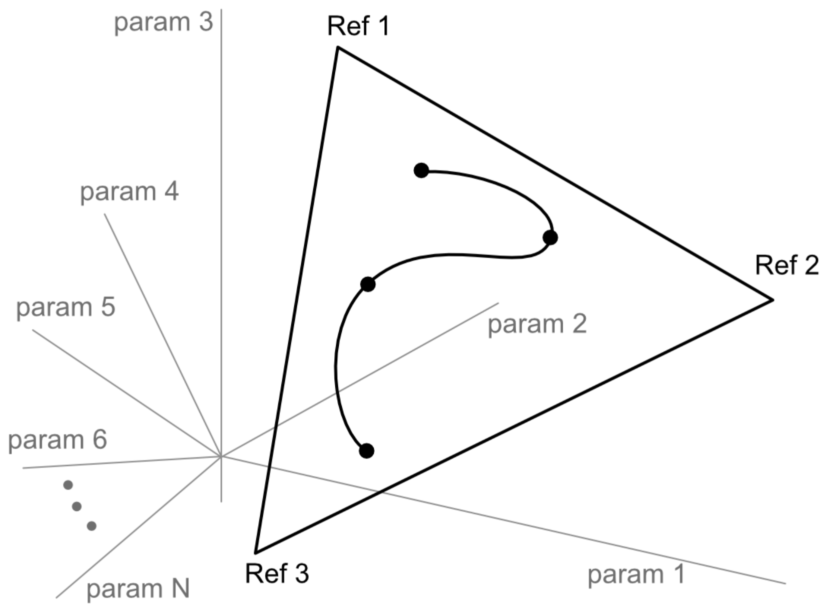
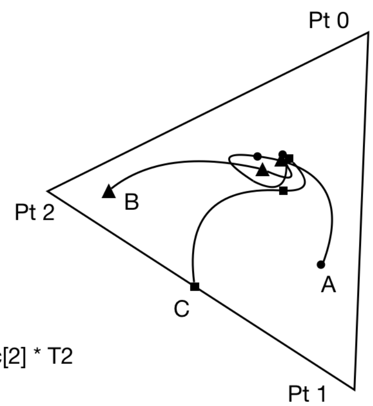


Figure 4.9: Spline connecting key points

the points calculated, to distract the spline from going to the stationary point. Also, the 'cut' of the spline happens with a certain probability, so the spline has to restart from a new fresh point. In this manner, the ever-ending sequence of the splines that go towards the stationary point can be generated repeatedly. The installation repeats loops of these short compositions, throughout the duration of the exhibition.

Ref Pt	Tendency	Cut
0	T0 = (0.7 , 0.2 , 0.1)	0.1
1	T1 = (0.4 , 0.2 , 0.4)	0.6
2	T2 = (0.4 , 0.3 , 0.3)	0.8



ex)

Current Coord: c = (0.3, 0.6, 0.1)

Next Coord: n = c[0] * T0 + c[1] * T1 + c[2] * T2

= (0.49, 0.21, 0.3)

A	B	C
(0.30, 0.60, 0.10)	(0.10, 0.10, 0.80)	(0.00, 0.50, 0.50)
(0.49, 0.21, 0.30)	(0.43, 0.28, 0.29)	(0.40, 0.25, 0.35)
(0.55, 0.23, 0.22)	(0.53, 0.23, 0.24)	(0.52, 0.24, 0.25)

Figure 4.10: Motion from transition probabilities

4.1.3 Result

In the creative process of *Reconstruction*, the state space model played a crucial role in finding the proper parameter values for intended visual and sound. By approximately setting first reference points, more precise values could be found easily with adjusting barycentric coordinates. After that, the coordinate of newly found parameter values became new reference points. Multiple iterations of this process enabled finding the optimal reference points for intended temporal control. Then with the finalized reference points, the semi-manual generative control could be designed, by connecting the points in the formed state space with splines and straight lines. It was also efficient to generate the temporal control with the state space since the code for temporal control signal generation only had to produce three numbers, the barycentric coordinate. In a way, the composition of the *Reconstruction* is a combination of the generative spline system and the manual choice of reference points and the transition matrix. This success with the *Reconstruction* led to a further attempt in the following work *Balanced Movement*, utilizing the state space interface for more delicate controls with more manual touch.

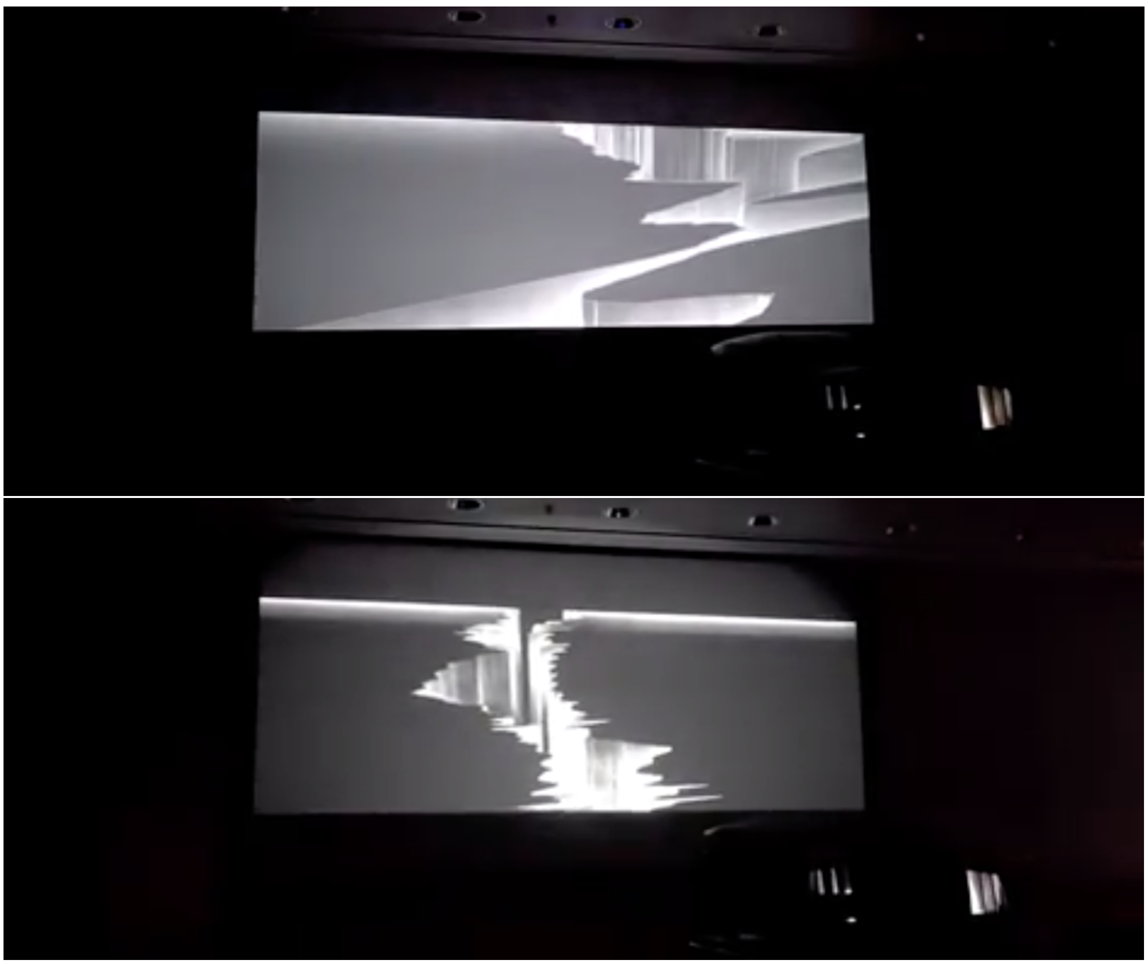


Figure 4.11: *Reconstruction* at EoYS 2018, UCSB

4.2 *Balanced Movement*

The *Balanced Movement* series started as visual experimentation on a stochastic process. Inspired by the work of Xenakis, it is an attempt on utilizing the dynamic equilibrium of a stochastic system for visual composition. The first iteration did not have temporal structure and was a continuous self-evolving system with constant parameters similar to those examples of the game of life [38]. The work presents three different visual elements, dynamically transforming into other elements according to the stochastic law they obey. Depending on the parameter values of governing law, different dynamic equilibrium can be achieved, and it will give different visual textures. After the *Reconstruction*'s experiment with the state space, it seemed promising that *Balanced Movement* could be evolved into work with temporal composition, also with audio accompanied. Hence the next iteration of the *Balanced Movement* involved reconstructing the implementation into a new implementation that is more easily controllable, as well as integrating an audio output logic that follows the visual from the amount and ratio of the three different elements. After the new implementation was worked on, with the state space interface, a temporal structure was be composed. The *Balanced Movement* was shown at MAT End of Year Show 2019 [39].

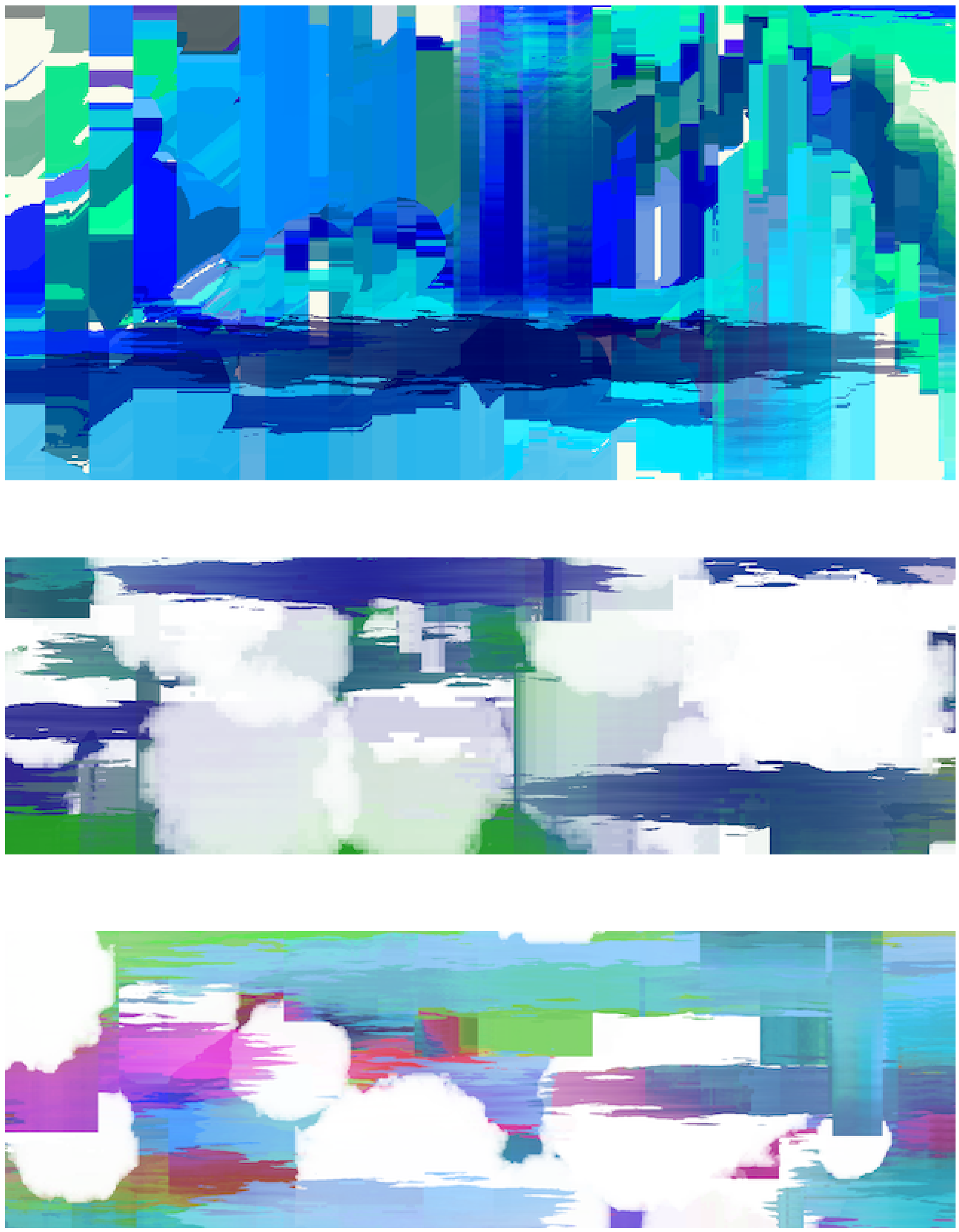


Figure 4.12: Initial iterations of the *Balanced Movement* series

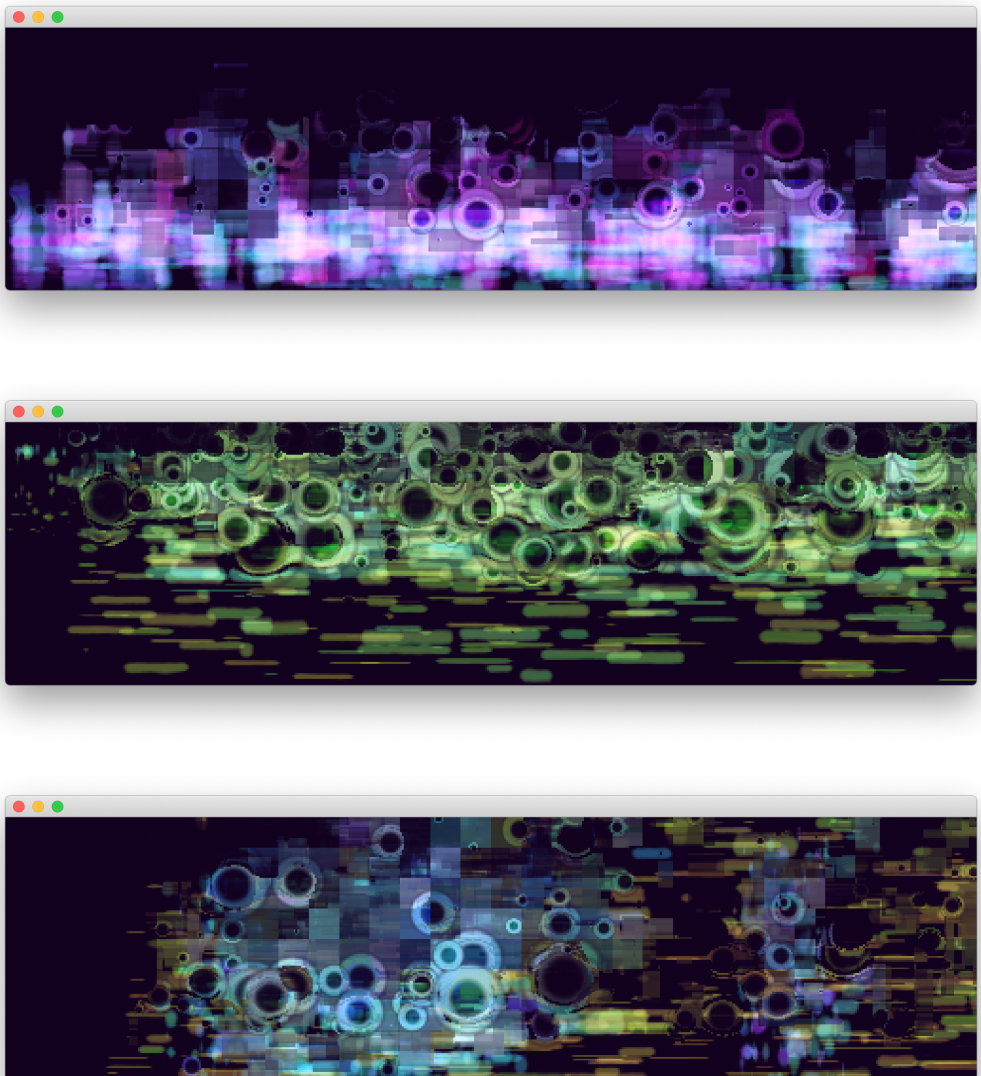


Figure 4.13: *Balanced Movement* 2019

4.2.1 Generative system

A three by three matrix can form a Markov system, each row defining the transition probability of the three elements of the system (figure 4.14). When an element is transitioning, it will change into other elements or stay in the same category depending on the transition probability of its kind given by the transition probability matrix. An individual transition of an element is a random process but with a large number of transition events a macroscopic behavior, the dynamic equilibrium emerges. When this process is run with visual elements, it can generate a unique texture with an almost uniform pattern being maintained throughout the canvas while having different details everywhere in smaller local regions. What makes each result unique is a different balance (ratio and amount) between the three elements. The ratio of this balance is determined by the steady-state of the transition probability matrix used to make transitions. This dynamic equilibrium also continuously changes in time while still maintaining the overall characteristic. This is where the title of the work comes from. While continuously there are movements and changes at the microscopic level but still on the macroscopic scale, it is balanced by the hidden governing system.

In this work, the three states are identified as ‘Generation’, ‘Modification’, and ‘Destruction’. The ‘Generation’ introduces a painting action on the canvas. It is the only element that can color the canvas on its own. The ‘Modification’ takes what is draw already and spread a modified version. It cannot paint by itself and only can with already existing ‘Generation’ element. As the name states, the ‘Destruction’ erases already drawn elements. If the transition matrix tends to produce more ‘Destruction’ elements, the canvas will be less dense, and in contrast, matrices that would make more ‘Generation’ and/or ‘Modification’ would fill the canvas with higher density. Their rendering style distinguishes the contrast between ’Generation’ and ’Modification’. The ‘Genera-

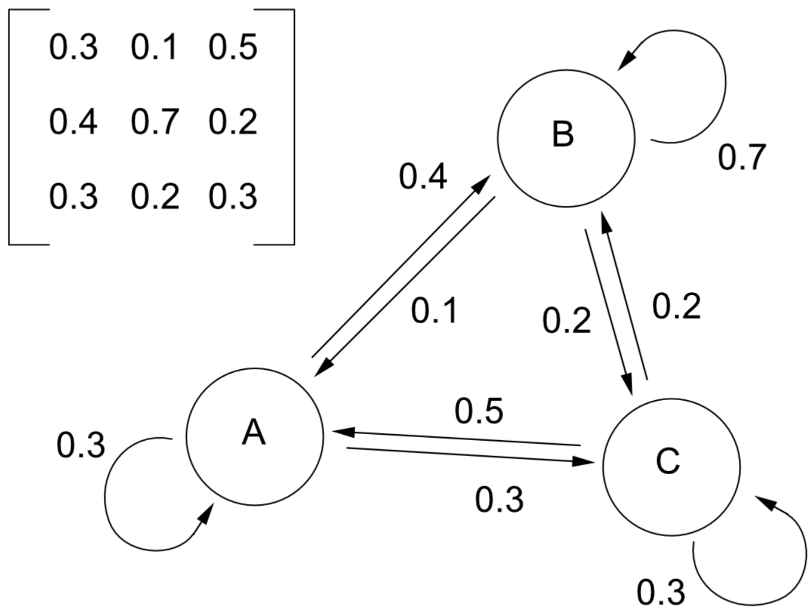


Figure 4.14: An example illustration of Markov system used

tion' renders in smooth brush stroke-like style, while the 'Modification' renders itself in pixelated flat colored style. Their geometry also distinguishes the elements: 'Generation' as horizontal, 'Modification' as vertical, and 'Destruction' affects a circular region. The elements share the same set of parameters, and for the graphical rendering, the parameters are interpreted differently depending on the type. Figure 4.15 shows the visual rendering of the elements and how the parameters are related to the visual.

The motion of the elements plays an important role in animating the texture of the canvas. The 'Generation' element makes a horizontal stroke, growing to the right side. Depending on its parameters, the 'Generation' can have a different thickness in the horizontal direction, different speed of growth, and a longer or shorter lifetime before the element makes the transition. The motion parameters of the 'Modification' element are orthogonal to those of the 'Generation' element. The element grows upwards and has the

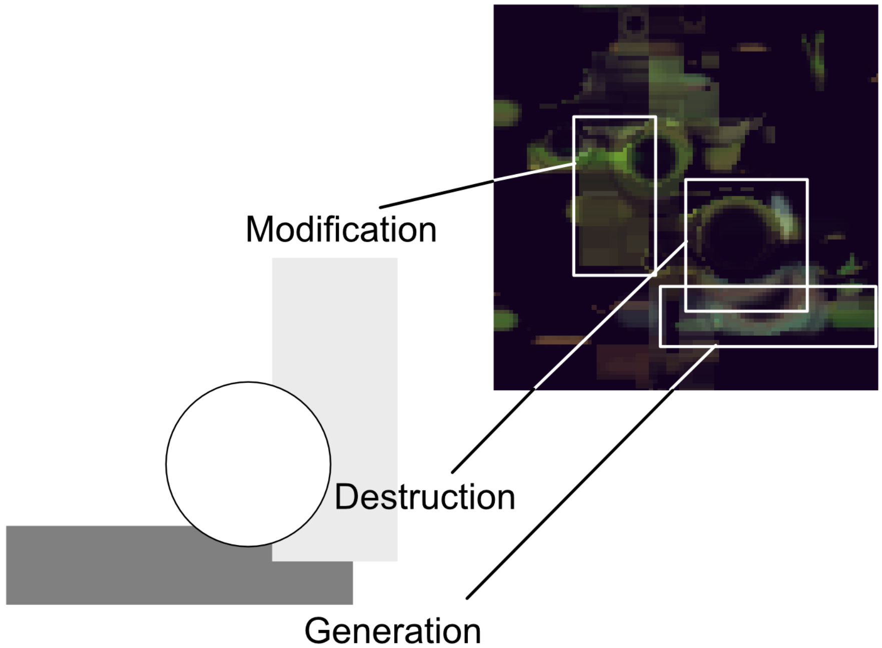


Figure 4.15: Examples of each visual element and its parameters

thickness parameter as the horizontal size. The speed of growth and lifetime relates to the same part as the 'Generation'. The 'Destruction' element grows to all four directions left, right, up, and down. It is a square shape that grows to be bigger in size. The size parameter determines the initial length of the sides of the square. The speed of growth and lifetime means same thing as the previous elements. The different motions of the elements gives the canvas more animated state. Since the motions of each element are distinguishable, when an element dominates the canvas, not only its shape will be cover the canvas but also the corresponding motion will animate the canvas. This motion of the canvas gives the work a more dynamic feeling.

The audio system follows the structure of the visual elements and thus consists of three instruments, just like figure 4.16. The first FM instrument is the same one that was used in *Reconstruction*, so it is skipped in the figure. Chirp and Chime instruments are modified versions of those in the example folder of Gamma sound synthesis library [32]. Each visual element has an audio element connected to it, and the parameters of each audio element depend on the group of visual elements of the corresponding type existing at the moment. For the 'Generation' element, the instrument is an FM instrument with vibrato on the modulator frequency, and three chorus passes. The 'Modification' is connected to the chirp instrument. The chirp is the sound from a short enveloped sine waveform. The instrument makes a cloud of chirps, spawning numerous chirps at different timings with randomized frequency. The instrument for 'Destruction' is a chime instrument. It presents pitched chime sounds, with predetermined frequencies.

To make matching for sound and visual, the parameters of the visual elements were translated to audio parameters. For FM instrument, parameters of the 'Generation' were used. The base frequency is mapped to the growth speed of the element. The vertical size of the element decides the overall amplitude. Since the 'Generation' element grows horizontally, the vertical size determines how much outstanding the element is on the canvas. The interval of triggering the FM instrument depends on how many 'Generation' elements there are on the canvas. A larger number of elements make the FM instrument to be triggered more frequently. The envelope duration of the FM instrument maps to a similar parameter of the visual element, the lifetime. The 'Modification' elements control the chirp instrument.

The frequency is mapped to the size of the element, and the amplitude to the number of 'Generation' elements on the canvas. Since the 'Modification' can only make visual when the 'Generation' is on the canvas, the same logic applies to the audio also. The probability of resetting the chirp is determined by the number of 'Modification' elements. Higher the probability, the instrument resets more frequently and more dense the sound becomes. With the chime instrument, the frequency comes from the predefined set of the notes: C0, F0, G0, A0, D1, F1, G1, A1, D2. The manually controlled offset of frequency will be added to these notes to give a different frequency range. The amplitude of the chime instrument is mapped to the size of the 'Destruction' elements, and the period of triggering the instrument depends on the number of 'Destruction' elements on the canvas.

```
function chirp

    if lfo looped

        if chance(0.1)
            randomize osc.freq

        if chance(0.001)
            randomize osc.decay

        if chance(p)
            reset osc

        if chance(0.008)
            randomize comb1.delay
            randomize comb2.delay
            randomize comb3.delay

        if chance(0.02)
            randomize chorus.rate

        if chance(0.01)
            randomize lfo.period

    raw = osc.sample
    filtered = comb1(raw) + comb2(raw) + comb3(raw)
    signal = chorus(filtered)

    return signal
```

```
function chime

    if lfo looped

        f = random [C4, F4, G4, A4, D5, F5, G5, A5, D6]

        osc0.(freq, amp, length) = ( 1.00 * f, 1.0, 1600/f)
        osc1.(freq, amp, length) = ( 2.76 * f, 0.5, 1200/f)
        osc2.(freq, amp, length) = ( 5.40 * f, 0.4,  800/f)
        osc3.(freq, amp, length) = ( 8.93 * f, 0.3,  400/f)
        osc4.(freq, amp, length) = (13.34 * f, 0.2,  200/f)

        randomize lfo.period

    raw = osc0 + osc1 + osc2 + osc3 + osc4
    signal = chorus(raw)

    return signal
```

Figure 4.16: Two of three audio instruments of Balanced Movement. Top: chirp instrument, Bottom: chime instrument

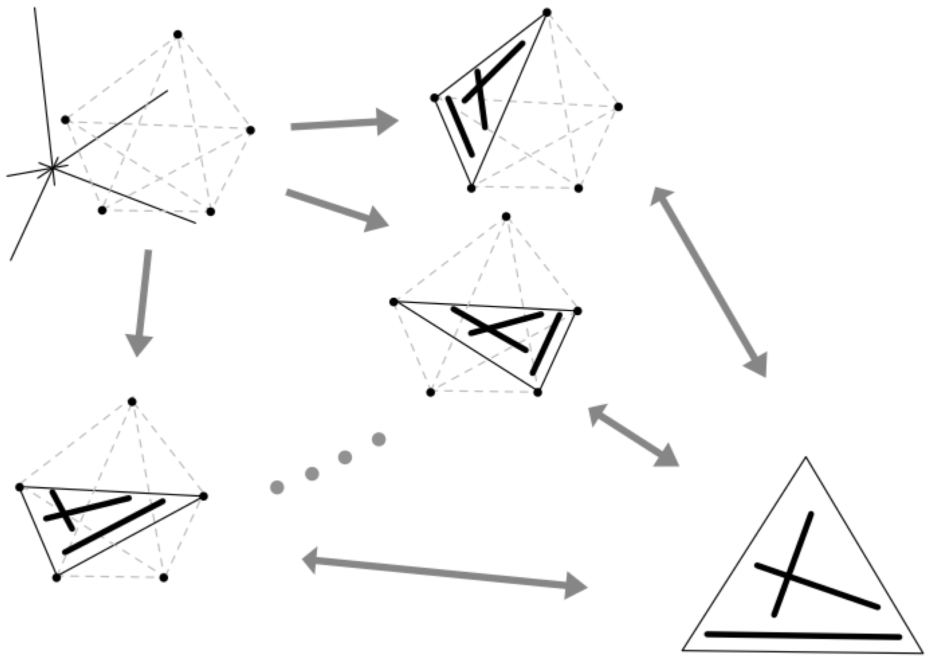


Figure 4.17: With the 5 reference points, selecting 3 points makes a set. Different sets can be used throughout the composition. The lines on the state space denote the motions performed with the barycentric coordinate. Note that they can be mapped to any sets.

4.2.2 Composition

The temporal control for *Balanced Movement* consists of two parts: motion and set. The motion is how the barycentric coordinate will move inside the state space. The set is a collection of three different reference points. With the motion and set, the parameter value for the system can be calculated. Since the motion depends on the set in which it is performed, the set can be considered as a higher scale structure. In this context, the stochastic system is the foreground, the motion is the middleground, and the set is the background.

Five different reference points are prepared and substituted in sequence to create different sets for compositional narrative on a large scale. Several motions are predefined for movements inside state spaces, creating middleground texture. The motions such as

```
composition << comp_action
{
    100, 100,                                  // Total length & fade length
    [&] () { vline(                            // Motion type
        {0, 1, 4},                             // Set used
        {0.0, 0.7, 0.3}, {0.2, 0.3, 0.5}       // Barycoord from/to
        {1.0f, 0.0f, 0.0f}, {0.5f, 0.0f, 0.0f}, // Audio mixer from/to
        80.0f,                                 // Motion durtation
        0.1f, 0.1f);                           // Geometry (x position & width)
    },
    [&] (int frame) {                          // Action done every frame
        if (bm_ptr) if (frame > 70) for (auto& e: bm_ptr->entities)
            e.x += e.speed;
    },
    fade_out_slow                              // Action done in fade time
}
```

Figure 4.18: Sample code for composition

sudden contrast, smooth transition, repeated short pulses are written with barycentric coordinate. Figure 4.17 shows how the reference points can be selected to create a set. Since the sets will be mapped to the same state space with three dimensional barycentric coordinates, the motions used can always be applied regardless of the set chosen. The motions used in the composition are linear movements from one barycentric coordinate to another. A combination of different sets and different motions enables the various temporal presentation of the change in texture: the different unfolding of the generative system according to its parameters. The technical implementation of the composition is as follows. The program keeps a list of actions. The actions contain information about which set to use and which motion to apply. The actions also have information about finer manual control decisions such as audio gain, and overall visual opacity. Figure 4.18 shows a screenshot of composition code with annotations and comments.

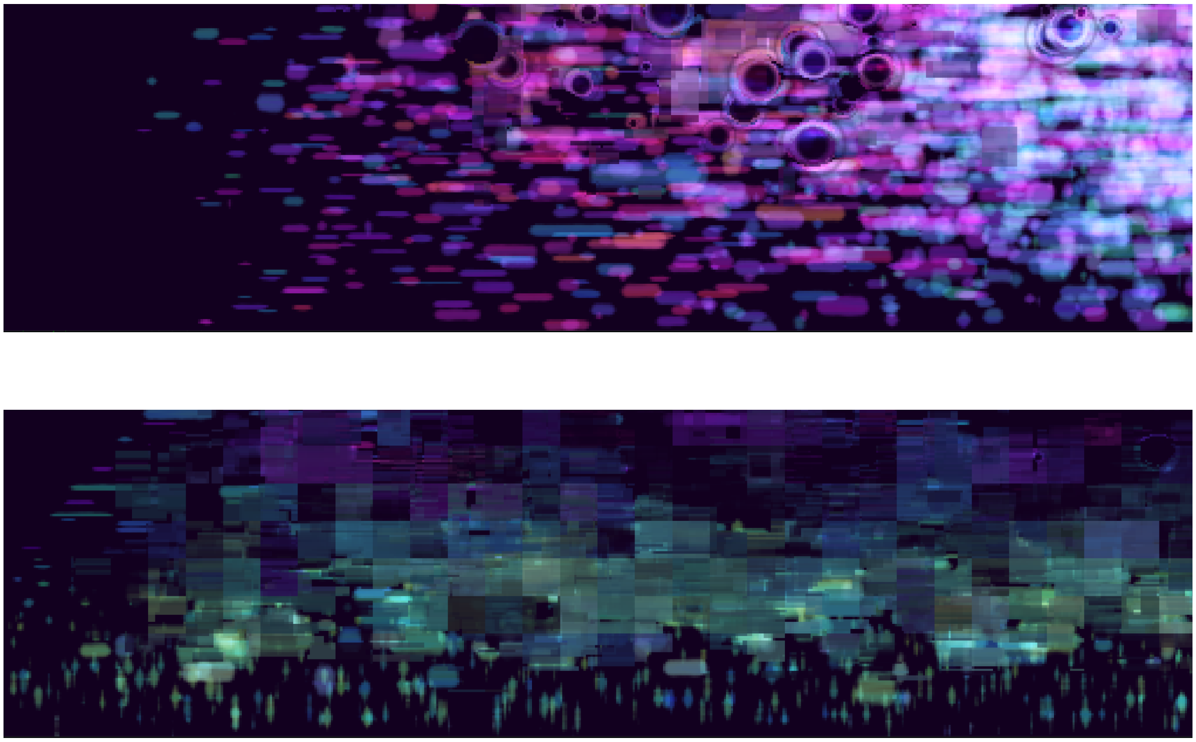


Figure 4.19: Composition of Balanced Movement, section1

The composition begins with set ⟨Pt0, Pt1, Pt2⟩ and three vertical lines. The first part introduces how the elements behave. The vertical lines stay at coordinate (0, 1, 0), thus showing Pt1. The lines fade away moving to the right, indicating the next two motions with horizontal sweeps to right and left. Horizontal sweeps also stay at Pt1. At the point when horizontal sweeps end, more dynamic motion is introduced. During a downward sweep motion the system state transitions from Pt1 to Pt2: the barycentric coordinate travels from (0, 1, 0) to (0, 0, 1). Up to this point is the first part of the composition. It introduces the elements, mostly 'Generation' and 'Modification', since the 'Destruction' is intended to come into play in the later parts. It also hints different kinds of motions that will be used in this work.

Next section presents a similarly structured motions but with different set ⟨Pt0, Pt2, Pt3⟩. Here the 'Destruction' element is introduced, and the overall intensity is raised

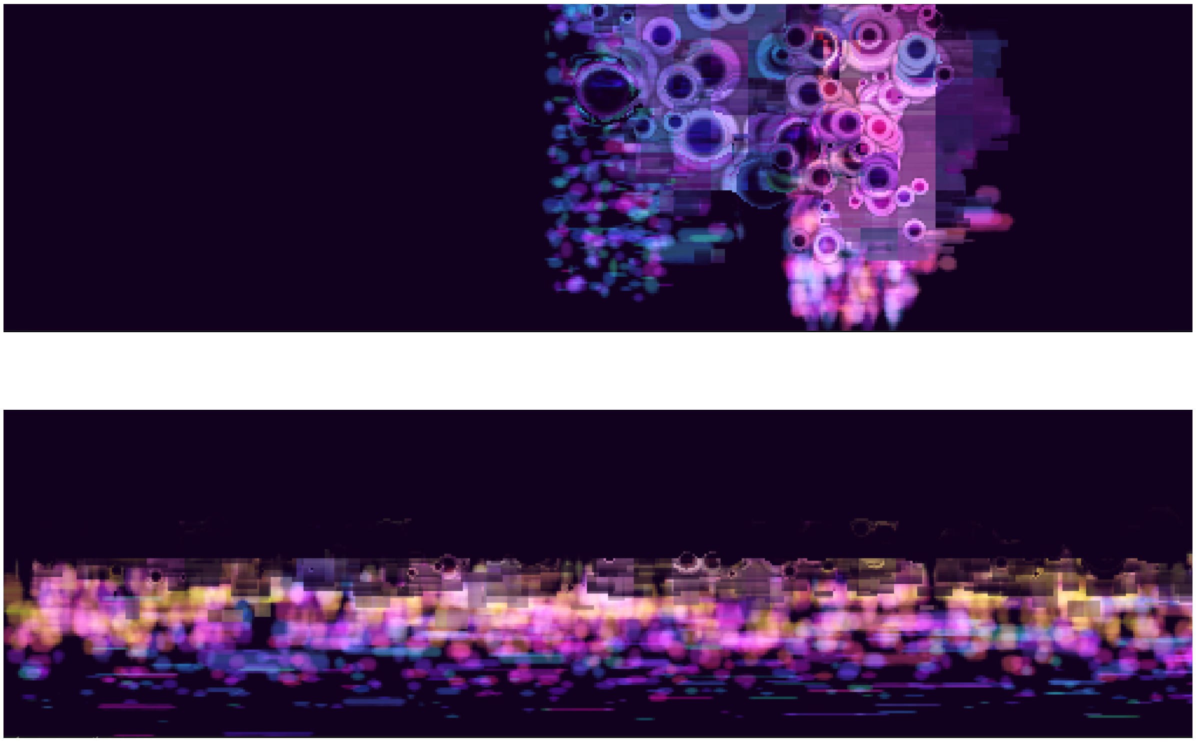
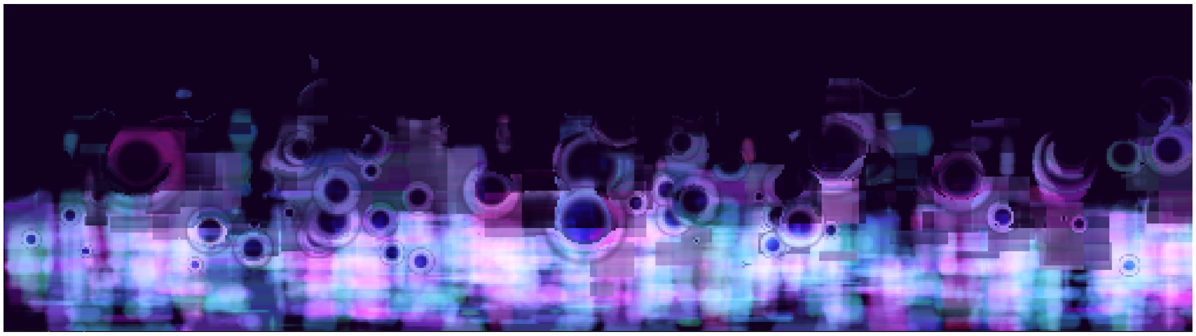


Figure 4.20: Composition of Balanced Movement, section 2

both in visual dynamics and audio complexity. The second section works as a connection between the second section and the third section. The barycentric coordinate travels between Pt2 (0, 1, 0) and Pt3 (0, 0, 1), while getting mixed with Pt0 (1, 0, 0) for change of intensity.

The third section contains the climactic point. It begins with contrasting motions from previous ones: horizontal lines. The audio with larger and denser chime sound drives the piece to its climax. The horizontal lines operate in the set ⟨Pt0, Pt2, Pt5⟩. Pt5 here presents thicker and heavier elements (high value for size parameter) which also gives a change of tone. The horizontal lines operate with barycentric coordinate moving from (0, 0, 1) to (0, 1, 0), first spawning large elements with Pt5 and then modifying them with Pt2. After the horizontal lines, The whole canvas gets filled with elements, with set ⟨Pt0, Pt2, Pt4⟩. Pt4 is the main phrase of the work, showing every element



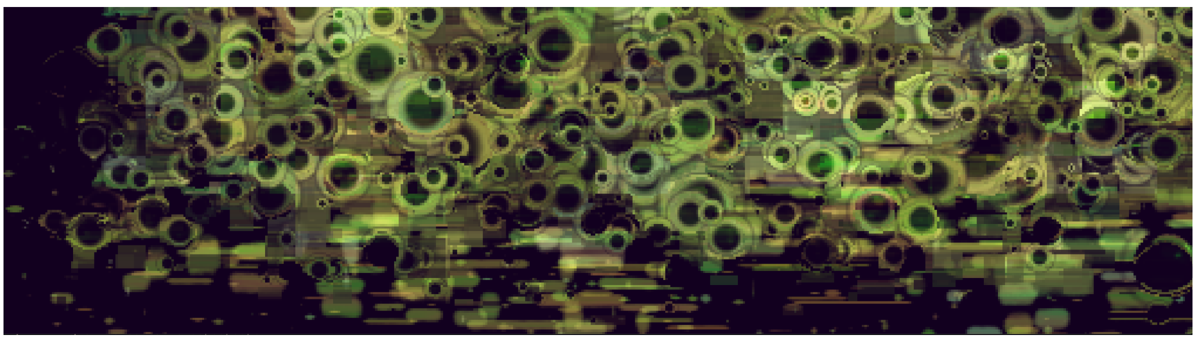


Figure 4.21: Composition of Balanced Movement, section 3

densely. The canvas starts to get filled with Pt2, coordinate (0, 1, 0), and transitions to Pt4, coordinate (0, 0, 1) by interpolation.

After the third section, the piece transitions smoothly to the fourth section. It being a continuation from third, the fourth begins with large chunks just like the beginning of the third. However, these chunks are spawned with $\langle$Pt0, Pt1, Pt2$\rangle$ and barycentric coordinate (0, 0.5, 0.5), driving the last section of the piece towards the first section. The piece ends with the opposite motion of the climax, sweeping up the elements from Pt4 and fading away to Pt0. The figures 4.19, 4.20, 4.21, and 4.22 shows sequence of the sections.

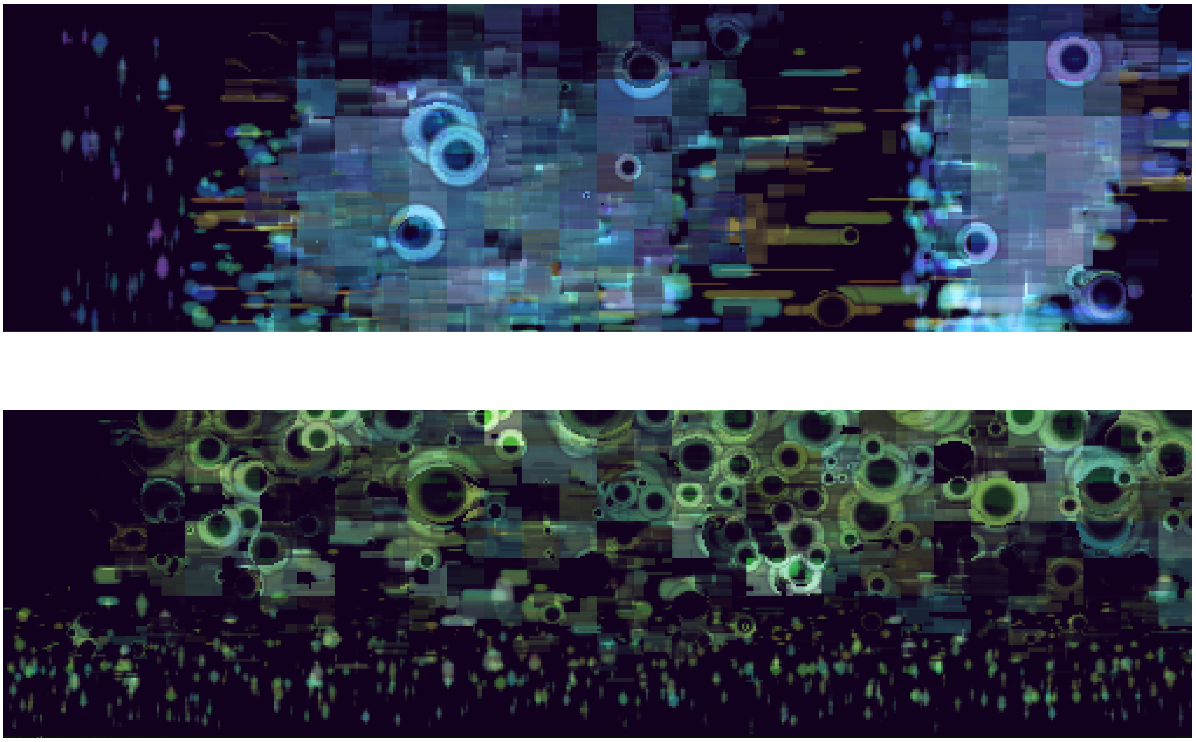


Figure 4.22: Composition of Balanced Movement, section 4

4.2.3 Result

The *Balanced Movement* presented the stochastic behavior of visual elements. Following the manual control on the transition matrix, different dynamic equilibrium was obtained and painted the canvas. The audio accompanied the visual to give more depth to the presentation. Compared to the first iteration of the series, it was the addition of audio and temporal control that gave the work a more effective presentation. Also during the renewal of the system, the elements were made possible to move on the canvas. This change was combined with the manual composition and presented more dynamic visual motion throughout the work. The motions also were used as hints for the following motion, making the presentation of motion sequences more coherent and more narrative.

During the composition process of *Balanced Movement*, the state space was effectively used to create middleground from motions and background from sets. The state space interface decoupled three different parts of the work — detail from the stochastic system, the overall motion of elements, and the macroscopic behavior of stochastic system — making the creative process efficient and effective but also connected them into a whole as one piece.

Balanced Movement is a work that shows a self-organization process in a manually controlled way. Many states of the somewhat unpredictable generative system were examined and tested in the creative process and then manually selected one that has interesting behavior was presented in a temporal structure to provide a composition. By presenting different outcomes of the generative system with continuity and contrast over time, the audience can compare the outcomes and understand the potential of the generative system. Since the goal of the work is to show how the stochastic system with a large number of elements can behave differently depending on the change in the parameters of the governing system, the narrative of the work designed with the state space interface effectively helped to achieve this goal.

Figure 4.23: *Balanced Movement* at EoYS 2019, UCSB

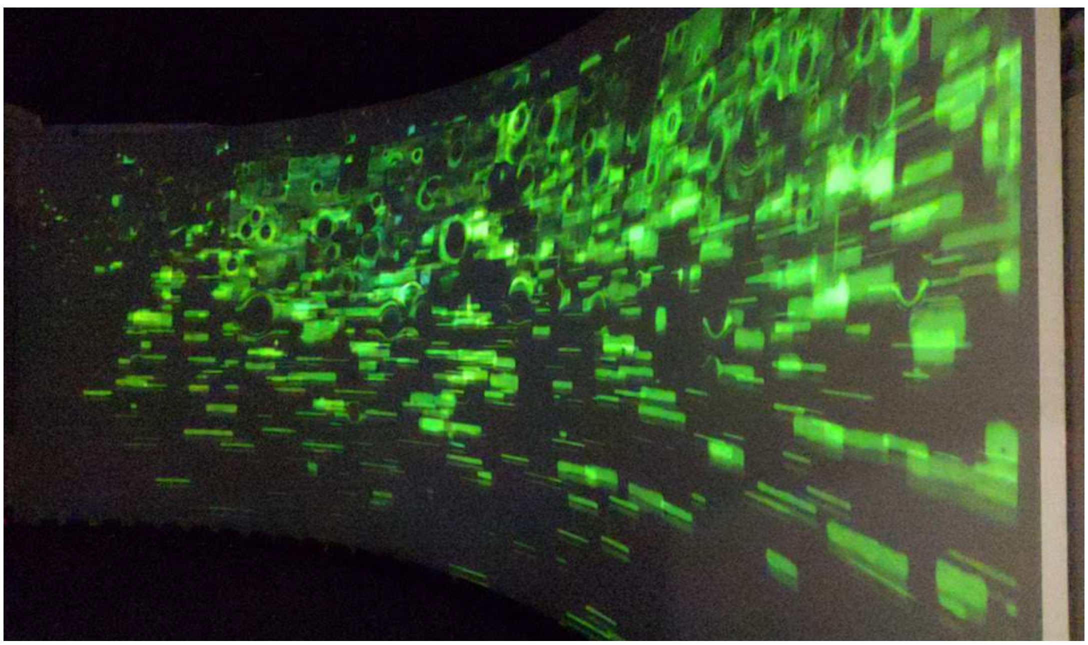


Figure 4.24: *Balanced Movement* at EoYS 2019, UCSB

4.3 *Wavefront*

The *Wavefront* is a real-time performance presenting full immersive stereo visual and multi-channel audio. It is run in the AlloSphere [20]. While two previous works in this research, (*Reconstruction* and *Balanced Movement*), involved a rather complex generative system with data processing or stochastic entity management, the *Wavefront* is only run by drawing very basic shapes in space. As the number of the shapes in space increases, the self-organization of the shapes as a whole is expected to emerge. To achieve this goal, the shapes are spawned with the rule decided by the performance time control signal.

The work is inspired by how a viewer observes an approaching ocean wave. Among many aspects of the ocean wave, it tries to present an interpretation of a specific part of the observation: the frontal surface of the wave. The characteristic of the frontal surface of an ocean wave is that though the wave is coming towards the viewer, the nearer part of the water surface is moving away, then rises, and eventually fall onto the viewer from above. This motion of contrast gives a unique experience to the viewer. While this behavior in the observation can be explained scientifically, the work does not calculate any physics of the wave, such as fluid dynamics, nor any analytic mathematics such as wave equations. Instead, the *Wavefront* tries to re-implement this phenomenon with a simple one-liner formula that produces the shape of a small wavelet and then spawn multiple of them to create a complex outcome. The formula is designed to be able to produce different development status of a wave, including swelling of the water in the beginning or breaking of the top part in the end. To explore the full potential of the AlloSphere immersive environment, the wavelets are turned into 3-Dimensional loops of polygons, animated along the moving direction.

Using the wavelet spawning system as an instrument, a compositional performance can be played. The state space interface is used to effectively control a large number of parameters in the performance time. By spawning many various shapes of waves with different direction and position, the immersive environment of the AlloSphere can be filled with the self-organizing phenomenon.

4.3.1 Generative system

The basic building block of the work is the shaping formula of the wavelet. As stated above, the formula is an arbitrary combination of terms to create the intended shape. The formula is:

$$let\, d = development \tag{4.1}$$

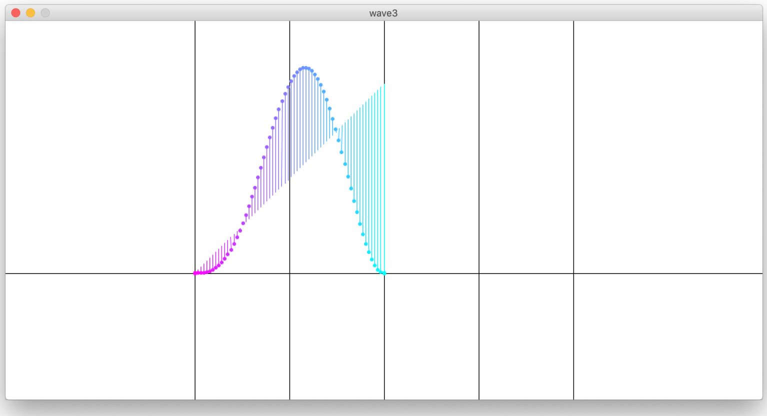
$$let\, r = reverse \tag{4.2}$$

$$let\, t = position\ on\ curve \tag{4.3}$$

$$x = -(1-r)*t - r*(1-t)*sin(2*\pi*t) \tag{4.4}$$

$$y = (1-t) - (1-t)*cos(2*\pi*t) \tag{4.5}$$

The formula has two parameters. The development connects to the life cycle of the wave. Value 0 of development is either the very beginning or the very end of the wave. Development value 1 is for the peak of the wave. The parameter reverse is whether the rear part of the wave travels faster than the front part and causes the wave to break. At reverse 0, the wave will just swell up and go down. At reverse 1 the wave will break, and the top part of the wave will fall down to the front. The result of this formula is shown with figure 4.25. The values in between will present states that are interpolations of each extreme. The parameter t, position on the curve, decides the relative position of the output point in the curve. At $t = 0$ the point is at the beginning the wave at bottom



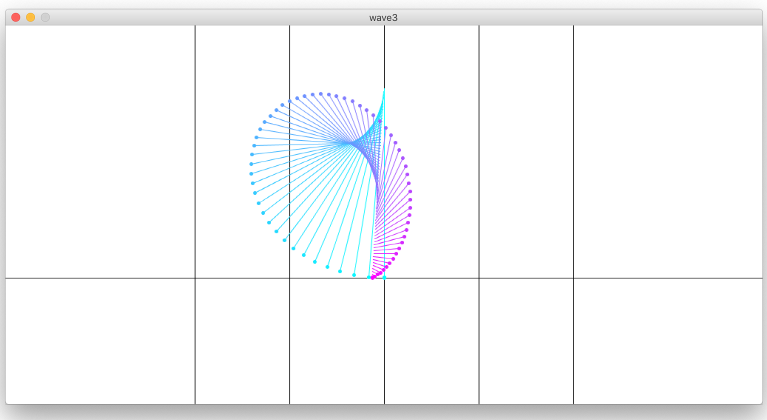


Figure 4.25: Top: development 1, reverse 0. Bottom: development 1, reverse 1

(colored cyan in figure 4.25) and at $t = 1$ the point is at the end of the curve (colored magenta in figure 4.25). Figure 4.26 also shows different outputs from the formula.

With the curve formula, three-dimensional wavelets are created. The process is to rotate several points on the curve along the ground axis to generate many concentric rings. The created three-dimensional wavelet travel along the axis direction. Figure 4.27 shows the diagram of this process. The rendering of the rings is done with custom OpenGL shader program to accelerate the rendering process as well as to obtain antialiased visual.

Figure 4.28 shows the rendered result. Instead of generating the polygon mesh consisting of triangles, the rendering method in the *Wavefront* uses the rounded line segments that are antialiased in the coloring process. This method enables the ring to be seen without artifacts regardless of the viewing direction, even when the rendering of the lines is done in two dimensional way. Compared to creating triangles to make a tube mesh, this method gives both quality and performance, especially for thick lines.

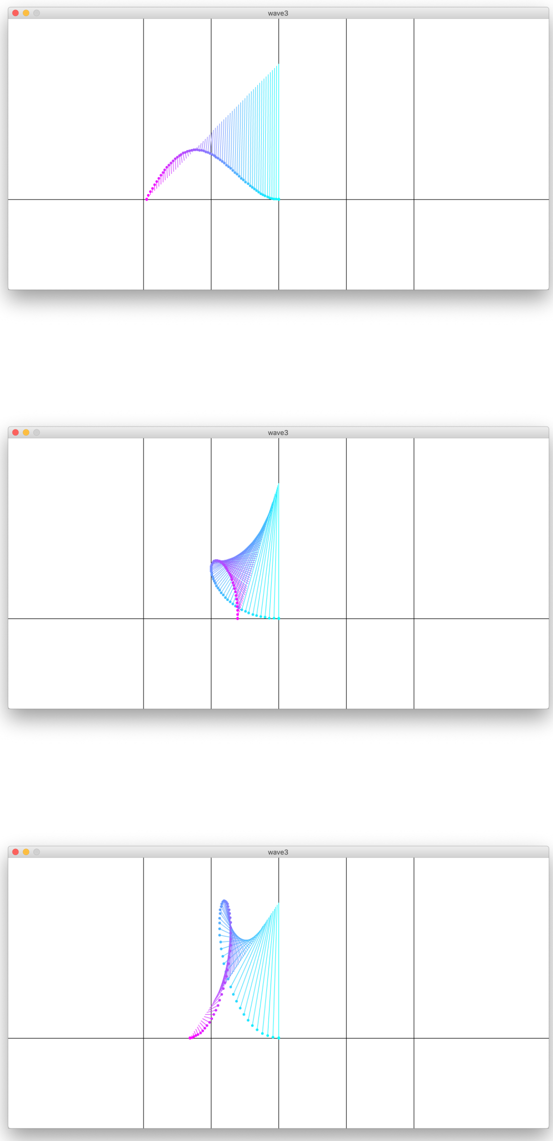


Figure 4.26: Top: development 0.5, reverse 0. Middle: development 0.5, reverse 0.7. Bottom: development 1, reverse 0.4

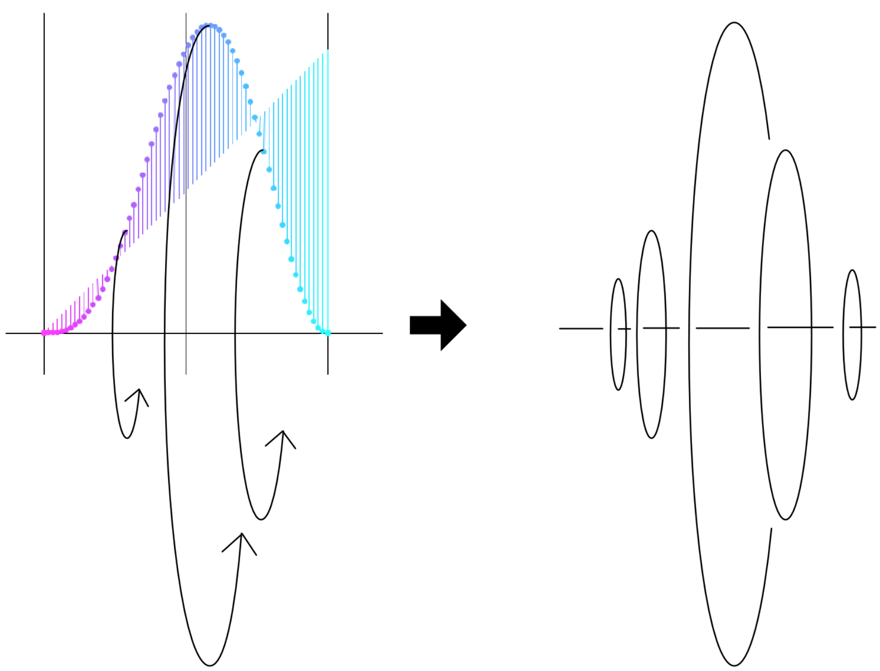


Figure 4.27: Creating three dimensional wavelet from the wave curve

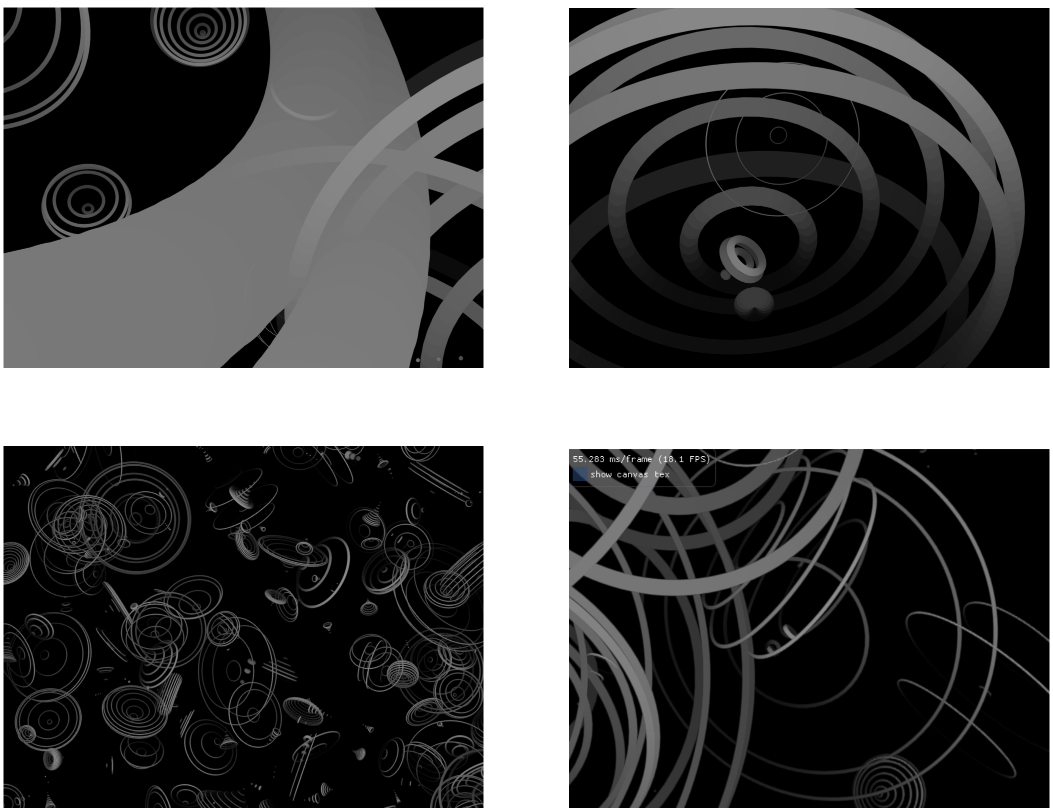


Figure 4.28: Rendering of the wavelets

The wavelet has 13 parameters. The *develope* and *reverse* is inherited from the curve formula. The *length* and *scale* controls the size of wavelets in the moving direction and radial direction orthogonal to the moving direction. *Thickness* and *sides* determine the geometry of the rings, how thick they are and how many sides they have. At $sides = 3$ triangle is generated rather than a circular ring. The maximum value of *sides* is 48. The *alpha* is how transparent the wavelet is. The *deltaphase* relates to how fast the rings follow the curve. Larger the *deltaphase* value, faster the rings will move. Finally, the lats parameter is the speed of the wavelet moving in space.

While the wavelets are very deterministic elements, how they are shot into space is controlled by a more flexible system. The spawn system brings in the metaphor of wind, just as the wind over ocean results in the waves to form. The wind has 10 parameters. The *number* and num_dev determines how many wavelets are spawned when the wind is triggered. The *buildup* and $offbeat$ decides the frequency of the wind triggering. The *buildup* is how much to add to the current wind value every update. When the wind value exceeds 1 (the threshold value), the wind is triggered. The $offbeat$ is the random deviation of the threshold value. When $offbeat$ is 0, the wind will be triggered periodically. Larger the $offbeat$ value, more irregular the wind trigger period will be. The *slope* and *dir* determines the wind direction. The *dir* is how much to rotate along the horizontal plane. The *slope* determines how much angle the wind direction is inclined relative to the vertical axis. When *slope* is 0, the wind direction is downwards, 0.5 horizontal, and 1.0 upwards. The *passdist* and *passdir* decide how far and which direction relative to the viewer (center) the wind passes when passing through the horizontal plane.

The audio system of the $wavefront$ utilizes the three-dimensional spatialization functionality of the AlloSphere. With the 54 channel audio system, the spatialization technique provided by the allolib is used. The sound sources travel with the wavelets while fading in and out as they approach and move away from the viewer. The instrument consists of four saw waves that are periodically triggered. They are added up and then enveloped with the main envelope. Then the signal goes through a chorus filter, then the spatialization process. When a sound needs to be spawned, 7 parameters are given to determine the instrument. The *attack*, *sustain*, $frequency$, and *amp* are just like the typical parameters of audio instruments. Then there is the *interval* which decides how often the saw waves are re-triggered. The $filter$ parameter is connected to the modulating frequency of the chorus filter. The *poly* parameter is used for calculating the amplitude weights for the saw waves. When the *poly* value is low, only the lower index saw waves are added up to create an output signal. The *poly* value of 1 is all the saw waves being added, and at 0.5, only the half of the saw waves are summed up.

For the performance setup, a Midi controller connected to Max7 software is used for the controls. The Midi signal from the controller is converted into OSC messages and then sent to the simulator application written with C++ and allolib. The simulator application receives the control signal and spawns the wavelets according to the parameters. Then the result of the simulation is sent to rendering machines for the visual and to audio interface with 54 channels for the audio. It is notable that the use of state space interface reduces the size of data needs to be sent. The configuration of the control signal will be discussed in the following section, *Composition*.

4.3.2 Composition

The composition of *Wavefront* is driven by the control signal from a Midi controller. There are three groups in the control signal. The first group determines the shape of the wavelet being spawned. Four sliders are connected to this group for locating a point in the tetrahedron based state space. This means that the system needs four reference points. Just like *Balanced movement*, there are more reference points than the dimension of state space so that the points can be swapped during the composition. A total of 6 reference points are prepared for shape control. The important difference between the presets is thickness, speed, reverse, and scale. This is due to the mapping of the parameters to the audio system. Thickness connects to the frequency of the audio. The reverse parameter changes the filtering effect and the scale parameter decides the sustain length. The speed parameter is important for visual composition. Figure 4.29 shows these 6 reference points.

The second group of control is for the wind parameters. The most important parameters for the wind system is the direction, number, and radius. Depending on the need of visual composition and audio spatialization, the direction of the winds change from top to front, left, right, and bottom. With the direction, how many wavelets to spawn and how much spread they will decide the visual composition of the work. Just like the wavelet shape reference points, there are 5 wind reference points and 4 of them are selected to create 4-dimensional state space. The directions of the 5 reference points are front, left, left, top, top-right, and bottom. Figure 4.30 is the diagram showing the spatial information of the wind reference points.

The first and second groups of the control consist of sliders so that the barycentric coordinate for shape and wind can be managed. The third group of the control consists of buttons that trigger the spawn (once for periodically) or the buttons that change the set of the reference points. Hence during the real-time performance, the performer first sets the reference points to be used with buttons, then adjusts the sliders on the controller to get the shape and wind intended, and finally spawns the wavelets with spawn button. By repeating this process, the performer controls two state space interfaces and is able to spawn the wavelets when needed.

The main narrative of the composition is to show how small individual wavelets are gathered to create a large scale phenomenon. Also, the work tries to show how much difference can be created in the large scale phenomenon from the small difference in the wavelets. For this narrative, the composition tries to contrast: spawning a small number of wavelets versus a large number of wavelets, fast wavelets versus slow wavelets, spawning wavelets with many rings versus a small number of rings, and breaking wavelets and non-breaking wavelets. The breaking of the wavelets involves a reverse motion to the direction of the movement. This reversing causes non-uniform movements that results in oscillating visual effect.

The composition begins with the wind set $(0, 1, 2, 4)$ and shape set (A, B, D, E). First, From wind 4 to wind 0, the direction of the wavelets shoot starts from below (4), and transitions to the front (0). The shape of wavelets moves from A to D to E. After arriving at the wind 0 (front), the shape set changes to (A, B, C, E). After, the wind jumps to 1 (left) and introduces the shapes A, C, D with set (A, B, C, D). The shooting from front and side each introduces various wave shapes and their movements, as well as the different sounds they create.

Then the composition moves to the main part. The wind set becomes $(0, 1, 2, 3)$ and the shape set is (A, C, D, F). The most important wind in this part is 2 (top). A large number of wavelets fall from above, filling the whole scenery. To give change in direction wind 4 (right) is mixed occasionally. Then the composition moves to ending part by coming back to front, with the wind set $(0, 1, 3, 4)$ and the shape set (A, D, C, E).

The key point in the controls of the composition is that when switching of the set is needed the barycentric coordinates for wind and shape are chosen that they are inside the common overlaps of the sets before and after. This resembles how the music composers move between different chords using the common notes between them.

4.3.3 Result

The *Wavefront* presented how the simple basic shapes can be animated and directed in space to create complex visuals. The ocean waves that are the inspiration of the work are re-interpreted into three-dimensional wavelets. The smallest material of the work is a deterministic curve formula, outputting different curves depending on the parameter values. The wavelets are created from curves, then are spawned with the generative wind system. The wind system periodically spawns a number of wavelets, in different spatial characteristics corresponding to the wind parameters.

The generative system of the *Wavefront* is much simpler than that of the previous two works. This simplicity requires more to be done on the compositional part. To experiment with control management, the format of performance was chosen rather than the static composition format. The state space control interface enables flexible control over the system in the real-time performance situation.

In the performance situation, it is not easy to control every parameter of the given system. The dimensionality reduction from the state space interface effectively limits the degree of freedom and gives the performer only the essential parts to be manipulated. What parts will be given by the system can be designed in the preparation time by the artist. Different state spaces can be prepared and used by switching between them throughout the performance, just like the chord progression or the key changing in the music composition.

The composition of the *Wavefront* in the performance time enabled the effective presentation of the generative system of the work. Without proper control over the system, the simple generative system of the work would have shown only repetitive and obvious results.

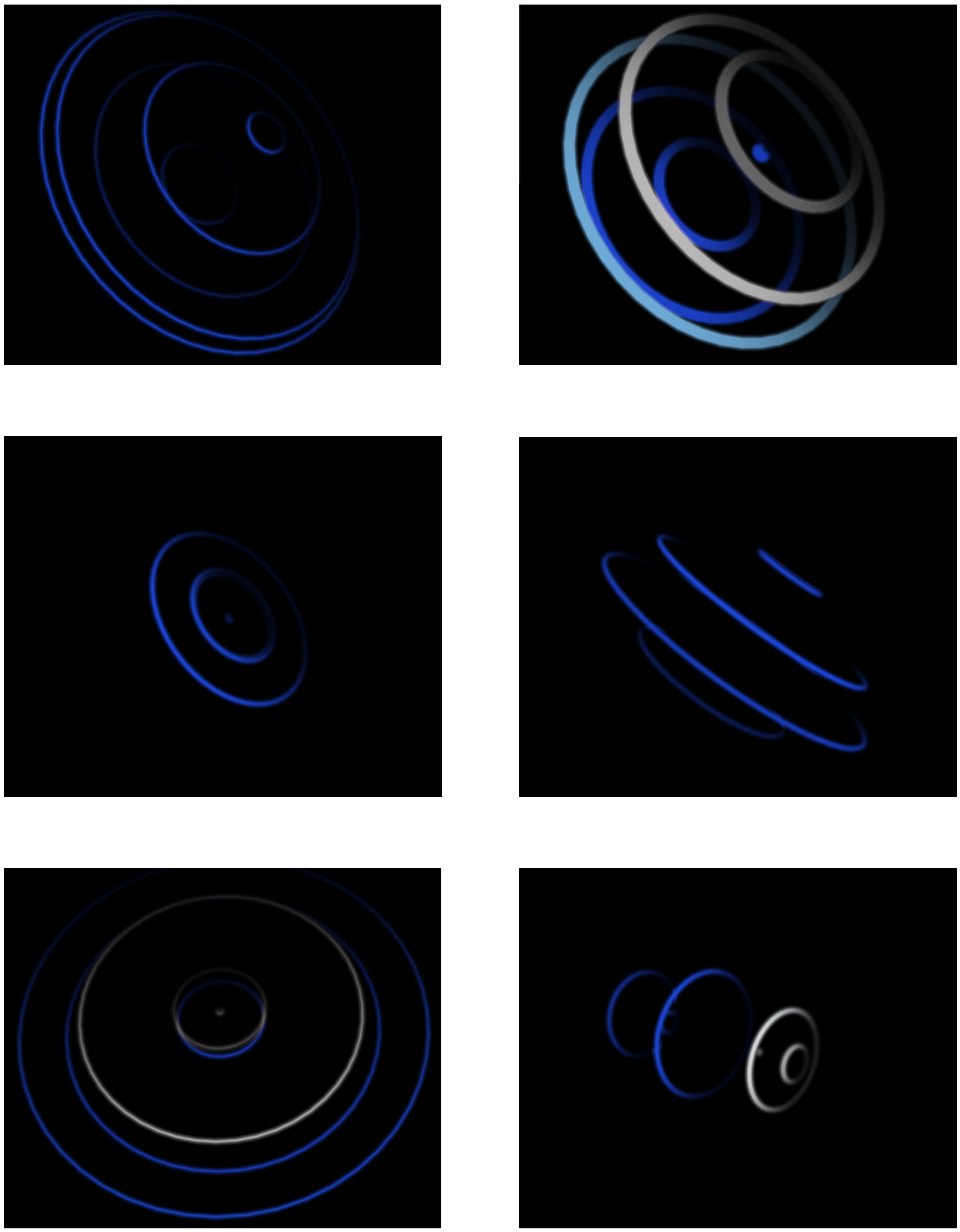


Figure 4.29: 6 shape reference points used for composition. Top to bottom, left to right, A, B, C, D, E, F

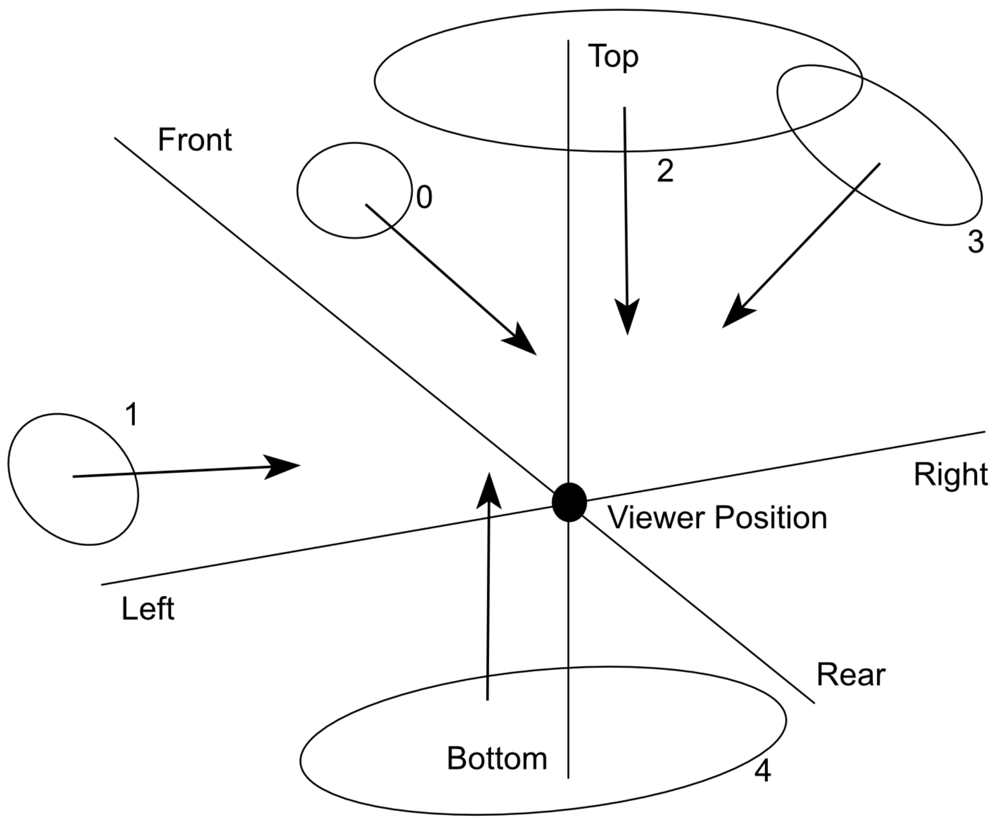


Figure 4.30: 5 wind reference points used for composition

Figure 4.31: *Wavefront* at EoYS 2019, UCSB

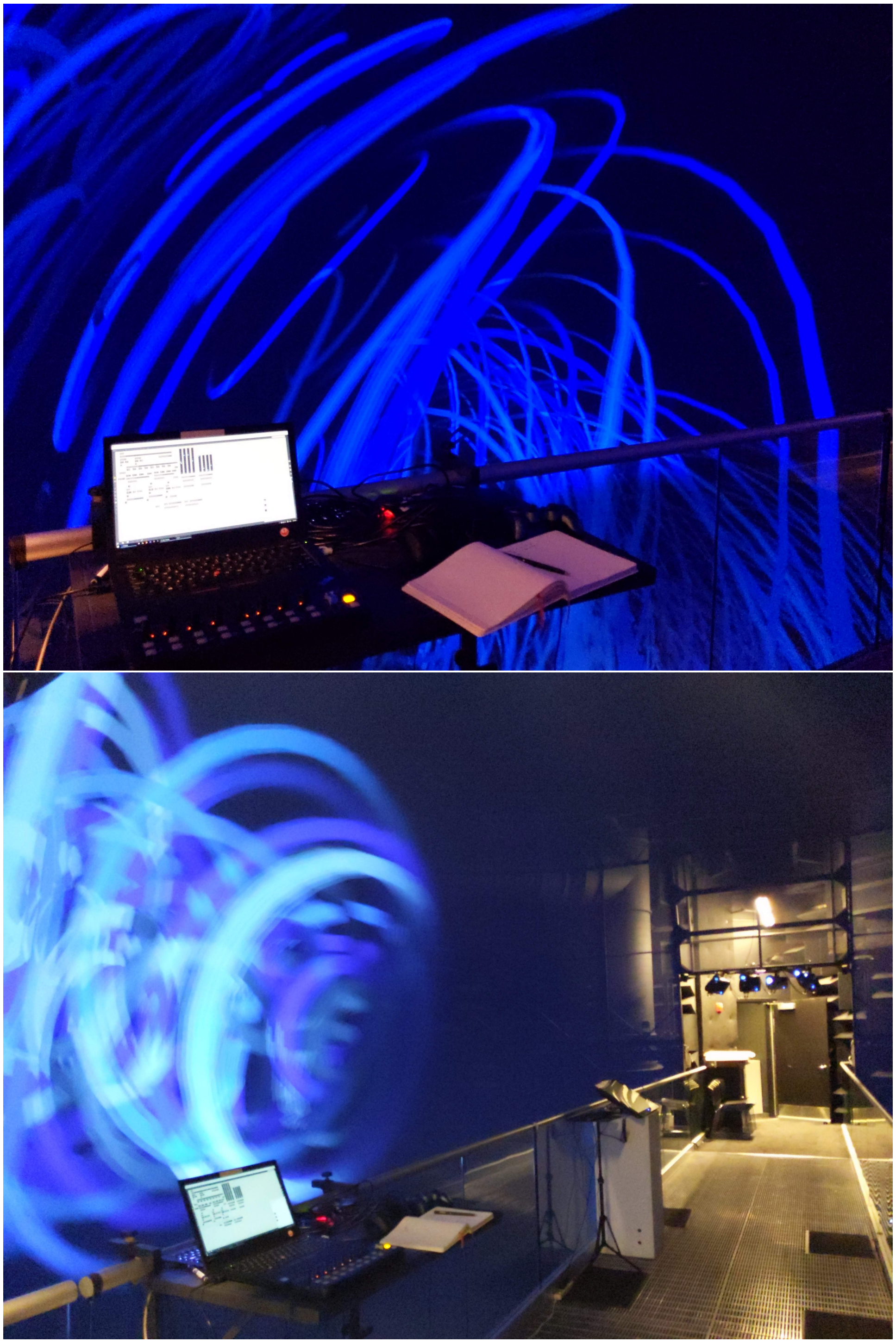


Figure 4.32: *Wavefront* at EoYS 2019, UCSB

Chapter 5

Conclusion

5.1 Discussion

The motivation of this research is to find a proper balance between the delegation of control and the manual management of control in the generative artworks. This motivation comes from the assumption that the generative system presented without any control will have a low probability of showing an emergent behavior. Hence the hypothesis of the research was “Effective interface for the manual temporal control could provide greater potential in aesthetic quality to generative audiovisual artworks”. To connect the two different layer of the creative process, the problem of managing a large number of parameters rises. To cope with this problem, a novel interface to manage parameters of the generative system was proposed: the State Space Interface. The proposed interface will be used as a connection between the generative system and the manually designed temporal composition, by effectively and efficiently managing the parameters of the generative system.

The state space interface is designed to facilitate the “divergent exploration and convergent optimization” in the parameter space, by applying a dimensionality reduction on the parameter space and constructing interpolation space with simplex geometry. Then with the constructed interpolation space, the barycentric coordinate is introduced to locate points in the interpolation space. When constructing the simplex, the reference points that are defined by the artist will be used as vertices of the simplex. The interpolation space is a space with a minimum dimension that can encompass the constructed simplex. The barycentric coordinate formed from the vertices of the simplex can locate any point in this interpolation space. With this mapping of parameter space to/from interpolation space, points in the interpolation space represent a mix of reference points in the parameter space, and they can be mapped back to the parameter space, to be used as input to the generative system. With this state space interface, the artist can use a barycentric coordinate to specify any mix of reference points. With this method of specifying the intended points, the artist can easily design the control signal. Mapping the control signal to the generative system is handled by the state space interface.

There are many advantages to the state space interface. First, it is not bound by specific dimensionality and has the freedom of choosing the dimension to work with. Also, the dimensionality of the interface and be flexibly adjusted. Next, the interface is computationally performant and efficient. Only one simple weighted sum formula is needed for every update frame. Moreover, the calculation is free of edge cases or specific conditions.

The state space interface does not abandon the previous methods of interpolation. Every related technique can still be used along with the proposed interface. While using the interpolation techniques, the state space interface also provides the removal of units and scales of the parameters, enabling a regularized or normalized coordinate system when designing dynamic motions in the state space.

The state space interface abstracts system state by hiding the actual parameters behind the barycentric coordinate. With this abstraction, the state space interface decouples lower-level details and higher-level structures of composition. In this scheme, the artist can design larger-scale structures manually with barycentric coordinates and then connect to the generative system that will follow the structures while creating smaller scale materials. The state space represents only a slice of the original parameter space. While this might be considered as a limitation, the constraint in the parameter space can be considered as part of the compositional process. By excluding the materials that are not needed, the artist can form a set of material for the composition. Also since the interpolation space can be constructed to have any dimension, the control is still in the hands of the artist.

Three works that utilize the proposed state space interface were introduced. The first work reconstruction shows how the motions in the state space can be used to create temporal structure in artworks. The Balanced Movement is about using the same set of motions that can be applied to different state spaces constructed from different sets of reference points. The Wavefront uses the state space interface as a performance control. A large number of agents can be spawned while their parameters are defined using the barycentric coordinates.

5.1.1 *Reconstruction*

Reconstruction is an audiovisual installation that shows an experiment on the reconstruction of a virtual geographic object from the observation data of a real one. The main goal of the installation was to present continuously in time different output of the work ever-changing. To achieve this the state space interface was used to interpolate between different reference points. After constructing state space with three predefined reference points, splines in control coordinate could be created to animate the system parameters. The creation of the trajectories was automated with tendency constants which govern the direction the system sate tends to move toward. It is the first work to try the state space interface for its temporal control. As a result, the installation could continuously present different shapes over time, with smooth or rapid transitions. However, while the *Reconstruction* utilized the state space interface, the work's narrative was not related to the question of this research: the balance between delegation and management.

The generative system of the *Reconstruction* was controlled by not manual composition but by another generative trajectory creation algorithm that operates in the state space with barycentric coordinate. In the context of this research, the *Reconstruction* was a proof of concept for the technical tool that will be used for this research. The separation between generative system logic and the parameter control signal was successful, and the connection of the separated parts by state space interface was also successful. *Reconstruction* showed the possibility of further development in the direction of this research, which was continued with the *Balanced Movement*.

5.1.2 *Balanced Movement*

Balanced movement is an audiovisual composition with the wall projection visual and stereo channel audio. Inspired by the *Pithoprakta* by Xenakis, the main motivation of the work is to visualize the generative system of a stochastic process with different kinds of visual elements on the digital canvas. Three different elements are represented by the corresponding drawing actions that fill the canvas. As they finish their action, they will make the transition to the next element, depending on the given transition probabilities The transition probabilities defined by the stochastic Markov system spawns the next element. Though the individual transitions are random processes, when these random transitions are gathered in large numbers, a dynamic equilibrium comes up. This dynamic equilibrium is presented with a unique texture pattern on the canvas, that is determined by the values of the Markov matrix. Presenting the unique outcomes of the stochastic process is the main narrative of the work. For the intended narrative, it is important to show differences and similarities of the textures while preserving the autonomy of the system.

The composition of *BalancedMovement* demonstrates how common motions are applied to different state spaces that are constructed from different reference points. By applying common motions to different state spaces, the composition shows how the generative system can morph locally (with motions, within the state space) or can show contrast with large change (with the change of the state space). Selecting a different set of reference points resulted in the different overall tone of the work. In this way, the composition should enable the effective presentation of the full potential of the system. The generative system will freely generate details while the manual control signal gives the larger temporal structure. In this manner, the state space from reference point sets becomes the background of the work, while the motions become the middleground of the work.

As a result, the Balanced Movement showed how a generative audiovisual material can be driven by temporal manual control, Effectively presenting the potential of the generative system.

5.1.3 *Wavefront*

The *Wavefront* is an immersive audiovisual performance run in the AlloSphere. The work tries to create complex spatial phenomena from the simplest shapes. The main inspiration for the work is the shape of ocean waves. A parameterized mathematical formula is used to create the different shapes of the waves from smooth and round wave shapes to breaking wave shapes. To fully utilized the immersive environment of the AlloSphere the wavelets were extruded into three-dimensional shapes.

In the performance time, the wavelets of different shapes are spawned by the performer's control. Along with the shape parameters, the parameters for the wind control (direction, the number to spawn, the affecting area, etc.) are also managed in the performance time. Two state spaces were used simultaneously for the different domains of the parameters. For shape parameters, a four-dimensional state space was constructed from picking four reference points out of six, and for wind parameters, also a four-dimensional state space was constructed from five reference points. A midi controller with knobs was used to control the barycentric coordinates of two state spaces. By presenting the different situation of the immersive scene in the AlloSphere, the work shows how simple system can create a visually complex result.

The $Wavefront$ also shows the capability of the state space interface in the realtime condition. Not only the computational cost is low, the barycentric coordinate as the result of dimensionality reduction is more efficient for a network system.

5.1.4 Result and Contribution

As a result, the state space provides an intuitive method of control with barycentric coordinate and scalability with flexible dimensionality choice. Also, it is efficient and productive in the creative process by virtue of the dimensionality reduction.

Overall, the proposed method in this research enables the connection between generative material and manual composition. Thus the contribution of this research to the field is done by developing a novel method to manage a large number of parameters for a generative system.

5.2 Future Direction

In the development process of *Balanced Movement*, there was a need for interpolating the transition matrices. It was shown that even if a parameter is not a scalar value, it can be well interpolated with the barycentric coordinate if a parameter specific interpolation function was provided. Since each row presents the probability distribution of the corresponding state, two rows from different matrices can be interpolated linearly. This is possible since the rows will always be on the `x + y + z = 1` plane. If this is generalized, one can provide any linear, non-linear, or any complex logic interpolation function for the parameter and at the same time just linearly handle them with barycentric coordinate. This process is effectively the same as distorting or warping the subspace of the state space, by stretching or shortening the axes. This topic of warping the subspace can further be researched for more capabilities of the state space approach.

Also, another possibility for future work is to use the motion in state space as modulation. Just as motion in the frequency domain enables Frequency Modulation technique, motion in the parameter space can provide more expressive methods for controlling the parameters. For example, circular motion in the state space with three reference points can effectively perform a "parameter modulation". Although the parameter modulation can be done without the state space model, the state space approach will have interesting capabilities. By tying all parameters together and modulating them all at once, the modulation can be controlled with the change in reference points. While parameter modulation is a very common and well-studied technique in the audio domain, it could provide new possibilities for the visual domain.

With all the different ways of utilizing the state space model, the long term goal of the research would be creating a rich collection of expressive methods with temporal structure this method provides. With the state space method, one of the great advantages in this regard is that this method enables the motions to be separate from the specific generative system. It enables the reuse of the motions for different generative systems. For example, with any state space from reference points of any generative system, a planar circular motion can be applied without any condition. After many attempts with creative processes, a personal collection of techniques with the state space model will be constructed. With that collection, one would be able to extract and refine a unique set of vocabularies out of many different techniques.

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